

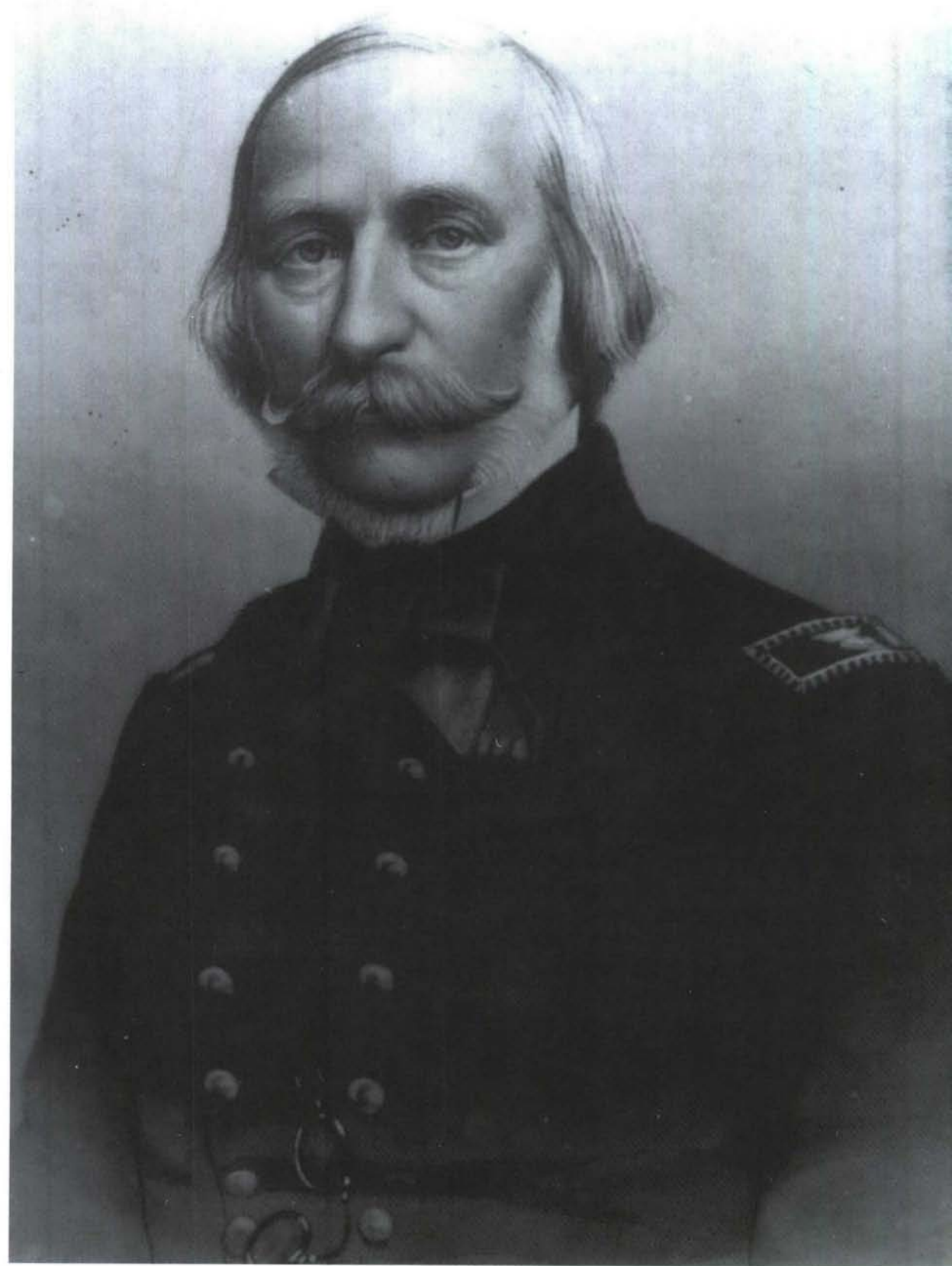
PROCEEDINGS
NAUTICAL ALMANAC OFFICE
SESQUICENTENNIAL SYMPOSIUM
U.S. NAVAL OBSERVATORY
MARCH 3-4, 1999

Edited by
ALAN D. FIALA
and
STEVEN J. DICK

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“There are tens of thousands of men who could be successful in all the ordinary walks of life, hundreds who could wield empires, thousands who could gain wealth, for one who could take up this astronomical problem [of an astronomical ephemeris] with any hope of success. The men who have done it are therefore in intellect the select few of the human race – an aristocracy ranking above all others in the scale of being. The astronomical ephemeris is the last practical outcome of their productive genius.”

–Simon Newcomb, “Reminiscences of an Astronomer” (Boston and New York, 1903), 63.

Frontispiece: LT Charles Henry Davis, USN, First Superintendent of the U.S. Nautical Almanac Office.

PREFACE

On the occasion of the 150th anniversary of the founding of the United States Nautical Almanac Office, the U. S. Naval Observatory hosted a three-day Symposium and associated activities beginning March 3, 1999. The choice of date was in itself an historical exercise, and March 3, marking the passage of legislation appropriating funds for an American almanac, was the first of several dates that might have been chosen. The Nautical Almanac Office actually came into existence when the funds became available July 1, 1849, and the first Superintendent of the office was appointed July 11. Work commenced still later that year, and the first volume was published in 1852. Still, March 3, when the Congressional appropriation set all these events in motion, is traditionally observed as our anniversary date. The details of this history can be found within this volume of *Proceedings*.

The Nautical Almanac Office was established as an independent entity, and became part of the older Naval Observatory only a half century later. Part of the rationale for establishing an American office was to remove dependence upon foreign almanacs, especially the British Almanac, and to join the ranks of the few major powers producing almanacs at the time: Britain, France, Germany, and Spain. Somewhat over a century later, the almanac offices of the United Kingdom and the United States became equal partners co-producing these major publications. Thus, it was symbolically appropriate that the Symposium and a banquet were held at the British Embassy, next door to the Naval Observatory. Attending the event were representatives from the almanac offices of the United Kingdom, France, Spain, and Japan, and greetings were sent from Russia.

The Symposium was planned to cover a broad spectrum of topics including the history of the office, its mission, the evolution of its products to meet contemporary needs, the users of those products, the underlying science, and the vision of its future. There was a conscious attempt to invite representatives of all aspects of our work: military and civilian, navigators and scientists. Over one hundred current and former members of the staff and representatives from other military and academic institutions attended, filling the hall to near capacity. The heart of the symposium was one and a half days of formal presentations, which are

preserved in these *Proceedings*. As part of the celebration accompanying the formal sessions, on Wednesday evening a reception was held at the Observatory for participants, friends, and staff, with remarks by Under Secretary of the Navy Jerry Hultin. Music was provided by a U.S. Navy Band combo composed of MUCM Gerard Ascione, MU1 John Parsons, MU1 Kenneth Carr, and MUC Randy Mattson. The banquet on Thursday evening featured an address by the Observatory's historian, Steven Dick, on the topic of extraterrestrial life.

The success of the event was due to the efforts of many people. The entire staff of the Astronomical Applications Department, currently the parent Department of the Nautical Almanac Office, contributed to planning and operations. Steve Dick was also heavily involved with the organizing committee. Other logistical assistance was provided by Annette Hammond, Lynn Treadway, and Dennis Baker from USNO, the Resources Management and Security Departments of USNO, and Carol Kaplan and Jill Bangert. Members of the British Embassy staff that assisted with arrangements were Commander Russell Pegg, Alison Latham, and John B. Nicol. John Bangert, Bob Miller, and Marie Lukac of USNO assisted in the preparation of copy for this volume. Thanks must also go to Captain Dennis G. Larsen, USN and Commander Mark J. Gunzelman, USN, respectively the Superintendent and Deputy Superintendent of the Naval Observatory during the anniversary, to Dr. Kenneth J. Johnston, the Scientific Director, and to all the participants in the symposium, whose cooperation made the symposium and this volume of *Proceedings* possible.

Alan D. Fiala and Steven J. Dick
October 1999

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HER MAJESTY'S NAUTICAL ALMANAC OFFICE

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Steven A. Bell

Donald B. Taylor

* Entered on duty May 1999.

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INTRODUCTORY REMARKS

John A. Bangert
U. S. Naval Observatory

Good morning. I am John Bangert and I am the Head of the U.S. Naval Observatory's Astronomical Applications Department. The AA Department is the modern-day parent organization of the Nautical Almanac Office. On behalf of the staff of the Department, I want to welcome you to this symposium that commemorates the 150th anniversary of the founding of the Nautical Almanac Office. Since its founding in 1849, the Nautical Almanac Office has enjoyed a proud history of service and accomplishment. Its main products—the almanacs—have been a critical resource, allowing safe navigation for ships and aircraft—both military and civilian—in times of war and peace. The history of the Nautical Almanac Office is also part of the rich tradition of the U.S. Navy.

But there is much more to this symposium than simply remembering the past. This gathering is also about the present and a look forward into the future. The symposium program reflects this. The organizing committee has striven to put together a full program of presentations that we hope you will find both interesting and stimulating.

Again I welcome you to the U.S. Naval Observatory and I sincerely thank you for helping us celebrate 150 years of service by the Nautical Almanac Office.

REMARKS AT THE NAUTICAL ALMANAC OFFICE SESQUICENTENNIAL SYMPOSIUM

The Honorable Jerry MacArthur Hultin
Under Secretary of the Navy

As a former Navy destroyerman, and a ship's navigator to boot, I am especially pleased to be here, celebrating the 150th anniversary of the Nautical Almanac.

I feel a strong kinship with you; as a navigator, I was a customer of the hard work all of you folks have put in to make navigation the precise tool that it is.

When I began to truly understand the power of navigation, I was a very young officer, with a limited background in celestial navigation (mostly from a course taken as a Navy ROTC student at Ohio State), often feeling alone at night on the bridge of my ship far at sea. LORAN didn't work in the South China Sea so we had to shoot the stars.

Gazing at the stars—which are spectacularly different out at sea—I felt a bond with those who had navigated before me.

Perhaps more, however, I felt a deep appreciation for those who had given me the right tools to navigate safely.

The right tools mean safety, national security, efficiency in commerce, the power to explore more effectively, and so many other things. Despite all these advances, there remain many challenges ahead of us.

We have come so far, just in the 150 years of the Nautical Almanac, and in the proud history of the Naval Observatory. We have every reason to be satisfied with our accomplishments.

But we must remain committed to further discovery, to exploration, to looking outward. And we will be.

With GPS (which I might add, is useless without the constant time updates the Naval Observatory sends to the GPS satellite system), we know where we are within 10 yards of the earth's surface, at all times. This is truly astounding—Galileo would be amazed.

But why, if this is true, does the occasional Tomahawk missile err from its course? Why does a Navy destroyer get rammed by another ship,

on a clear night, with dozens of good people on watch—as was the case recently?

Perhaps our challenge now, for all of us, is to shift our view. Navigation is a wonderful tool—for our armed forces, for a host of new civilian applications that will make our lives even better.

But perhaps we need to look more closely at its application; how we use it more effectively and how we can attack the human failings that surround its wonderful achievements. That is up to each of us, here.

It is perhaps time to go beyond incremental change, and to look at a fundamental change in our thinking.

Let's revel in our achievements—there is nothing wrong with congratulating ourselves—we deserve it!

But let us not forget that young Navy Lieutenant on watch tonight, who is gazing at the heavens from her bridge (as I once did not so very long ago). She is a highly trained professional, and proud of her ship and what it can do—but rest assured, even in 1999, she is thinking what all mariners have thought for centuries: “A collision at sea can ruin your entire day” (Thucydides).

There is much work to be done, with the Almanac in the next 150 years, and with the way we approach navigation generally.

I look forward to joining with you in meeting those challenges and I thank you for making my day, for giving me the opportunity to be with you to celebrate this occasion.

REMARKS ON THE OCCASION OF THE 150TH ANNIVERSARY OF THE AMERICAN NAUTICAL ALMANAC OFFICE

RADM Winford Ellis
Oceanographer of the Navy

150 years ago yesterday, on March 3, 1849, legislation was passed authorizing the United States Navy to produce an American Nautical Almanac. As we gather on the occasion of that anniversary, I cannot help but think how much navigation and science in the Navy have changed. Back then, the almanac, chronometer and sextant were essential to navigation, but could still leave a ship many miles off course. Now the Global Positioning System of satellites circles the Earth, and precise time, astrometry and a detailed knowledge of Earth Orientation allow us to navigate within a few meters. Back then, the Naval Observatory and Hydrographic Office were one small institution located in Foggy Bottom. Today, the Headquarters of the Naval Observatory and the Naval Oceanographic Office are still together side-by-side, now here on Massachusetts Avenue. But their telescopes, oceanographic ships and personnel span the globe, studying the oceans of the world and observing other worlds in the ocean of space. Back then, Lieutenant (later Admiral) Charles H. Davis, the founding Director of the American Nautical Almanac Office, spoke of “Sky with Ocean Joined” in the service of navigation. Today the concept of “Sky with Ocean Joined” is even more important as we carry out our daily duties of scientific support to an enormously more complex Navy.

The founding of the Nautical Almanac Office in 1849 was an important step in American science. The Naval Observatory and Hydrographic Office had been founded 5 years earlier, and was well on its way to becoming a world-class institution under the Superintendency of Matthew Fontaine Maury, now known as the founder of oceanography. But never before had American astronomers and mathematicians been brought together to focus on what turned out to be the greatest mathematical achievement of American science in that era—the American Ephemeris and Nautical Almanac. It WAS a great achievement, and those who participated knew it. Simon Newcomb, the most famous Superintendent of the Nautical Almanac Office, wrote

There are tens of thousands of men who could be successful in all the ordinary walks of life, hundreds who could wield empires, thousands who could gain wealth, for one who could take up this astronomical problem [of a Nautical Almanac] with any hope of success. The men who have done it are therefore in intellect the select few of the human race,—an aristocracy ranking above all others in the scale of being. The astronomical ephemeris is the last practical outcome of their productive genius.

Newcomb was known for many things, but not for lack of self esteem!

It is very appropriate that we should hold this celebration at the British Embassy, because of the long-standing tradition of cooperation between the British and American Nautical Almanac Offices. I take this opportunity to thank our British hosts.

The modern Nautical Almanac Office, its parent Astronomical Applications Department, the Naval Observatory—in fact all of us—have had to adjust to the rapidly changing world around us. As we look back on our past achievements today, we also look forward to the new challenges that are bound to come. I am therefore pleased that the program today and tomorrow not only looks back, but also looks forward.

I offer my congratulations to the Nautical Almanac Office and the Naval Observatory on having reached this landmark. Best wishes for a stimulating and pleasant meeting.

LETTER OF GREETINGS

Victor K. Abalakin
Director, Pulkovo Observatory

4 March 1999

Dear Friends and Colleagues:

On behalf of all scientists of the Central (Pulkovo) Astronomical Observatory of the Russian Academy of Sciences I extend to all of you as well to your families our All-the-Best wishes on occasion of the remarkable event in the history of the world astronomical community - the 150th Anniversary of the U.S. Nautical Almanac Office at the United States Naval Observatory. We are happy to emphasize the outstanding role the U.S.N.O. has played and is playing now in advancement of the theoretical fundamentals of modern Positional Astronomy and their practical applications. The stellar catalogues based on observations made and analysed by the U.S.N.O. astronomers, and compiled in the U.S.N.O. are our mighty beacons of hope on better future in these dusk times for Russian stargazers.

I wish you good luck and success in your work and in celebrating your wonderful Jubilee.

With every good wish, I remain,

Cordially yours,

Victor K. Abalakin

Director, Pulkovo Observatory

DEDICATION OF THE HISTORY SESSION TO

LEROY E. DOGGETT

1941-1996

Dr. LeRoy E. Doggett was a staff astronomer of the U.S. Nautical Almanac Office from 1965 until his death in 1996, at which time he was Chief of the Division within the Astronomical Applications Department. He was an expert in calendars, astronomical phenomena, planetary theory, and the history of astronomy.

Dr. Doggett was born in 1941 in Waterloo, Iowa. He received his B.S. degree from the University of Michigan in 1964. He joined the staff of the Nautical Almanac Office of the Naval Observatory in 1965. He received his M.S. degree from Georgetown University in 1970, and his Ph.D. from North Carolina State University in 1981. His doctoral dissertation was on the use of Chebyshev series for a high-precision theory of the motion of Mars.

For the last 20 years of his life LeRoy compiled and edited the U.S. contributions to *The Astronomical Almanac*, *The Nautical Almanac*, and *The Air Almanac*, which serve as the world standards for ephemerides for astronomy and navigation. During that time he led the U.S. work involved in the change of format and content of *The Astronomical Almanac*, formerly *The American Ephemeris and Nautical Almanac*. He was also instrumental in converting the production of that publication to all electronic typesetting, with resulting reduction in errors and advance of production schedules.

Dr. Doggett's recent work centered on calendars and the history of astronomy. He wrote the chapter on calendars for the *Explanatory Supplement to the Astronomical Almanac* and was working on a book on the history of calendars at the time of his death. He was also editor of *Archeoastronomy* and organizer of the nationwide "Moon Watch" program to determine earliest visibility of the lunar crescent. He was active in the Historical Astronomy Division and the Division on Dynamical Astronomy of the American Astronomical Society, as well as the Institute of Navigation and the International Astronomical Union. He was a member of IAU commissions 4, 7, and 41.

LeRoy died on 16 April 1996. He had been fighting cancer since the previous November, but had been able to work at least on a part-time basis until eleven days before his death.

The Historical Astronomy Division of the American Astronomical Society has established a prize in his name, and Minor Planet (6363) Doggett was named for him.

He would have dearly wanted to be here for this celebration, we miss him, and we dedicate this session to his memory.

HISTORY OF THE AMERICAN NAUTICAL ALMANAC OFFICE

Steven J. Dick
U. S. Naval Observatory

The American Nautical Almanac Office is rich in history from many perspectives: as one of the oldest scientific institutions in the U. S. government; for promoting American navigation; for its many scientists, mathematicians and “computers” who deserve to be better known; for its leading role in international cooperation in science; and, not least, for its role in advancing astronomy in areas including planetary theory, astronomical constants, ephemerides and related fields. Although it is not possible in this brief paper to touch on all these subjects, there is perhaps merit in attempting a coherent account of the highlights of the 150 years that we celebrate today.

In order to provide an overview, I divide the history of the Office into three broad eras: the Founding Era (1849-1865), the Transition and Newcomb era (1866-1897), and the Twentieth Century. These three eras were played out, respectively, in Cambridge (Massachusetts), Washington, D.C., and at the U.S. Naval Observatory’s present location on Massachusetts Avenue in Washington.

Cambridge, Massachusetts: The Founding Era, 1849-1865

An obvious first question is why the Americans required their own Nautical Almanac when the British had been publishing a *Nautical Almanac and Astronomical Ephemeris* since 1767. Clearly one reason was grounded in patriotism. Already in his report of November 25, 1844 — two months after he appointed Matthew Fontaine Maury Superintendent of the Depot of Charts and Instruments (soon to transform into the Naval Observatory) — Secretary of the Navy John Y. Mason noted that the Depot’s new astronomical instruments were “well selected, and may be advantageously employed in the necessary observations with a view to calculate nautical almanacs. For those we are now indebted to foreign nations. This work may be done by our own naval officers, without injury to the service, and at a very small expense.” In his first annual report as Superintendent, Maury himself argued for an American

almanac as part of his goals: "If we attempt to compute the 'American Nautical Almanac' — and this we can do at no greater expense than we pay the English for computing theirs for us — from our own data, it is highly desirable that the data should be wholly American." Mason renewed this call for action on an almanac in 1846 and 1847, and in 1848 submitted estimates of \$6000 "for calculating, printing and publishing the Nautical Almanac, including pay of superintendent of the same." As Waff documents in detail in his paper in this volume, during this time Maury played the leading role as advocate of an American Nautical Almanac, shepherding it through a tortuous political process. Finally in 1849 — in the closing days of Mason's tenure as Secretary of the Navy, and on the last full day of James Polk's tenure as President of the United States — the Nautical Almanac was approved.¹

The naval appropriation act of 3 March, 1849 authorizing the preparation and publication of the Nautical Almanac was part of a paragraph relating to Maury's Hydrographic Office. It provided only "That a competent officer of the Navy not below the grade of lieutenant, be charged with the duty of preparing the nautical almanac for publication;" the remaining clause referred to the other business of the Hydrographic Office.² As the wording made clear, however, the Nautical Almanac was to have its own Superintendent, and when the appropriation became available the next fiscal year (beginning July 1), Lt. Charles Henry Davis (Frontispiece) was officially placed in charge effective July 11.

Although the act said nothing about the establishment of a distinct office, not only was the Nautical Almanac Office formed separately from the Naval Observatory and Hydrographic Office, it was founded in an entirely different city. Though one might have thought the new Office would immediately be associated with the Naval Observatory, or at least located in its proximity, there was considerable rationale for its location in Cambridge. Davis (1807-1877), a Boston-born 1825 graduate of Harvard, had lived in Cambridge (when not on sea duty) since 1835, engaged in the Coast Survey work. Harvard University was near, with Benjamin Peirce and other mathematical talent, and its library, enriched with the library of Bowditch, was important. The mathematical work of the Nautical Almanac Office differed significantly from the observational work of the Naval Observatory, requiring only the data from the latter and not a physical presence at the Observatory. And although Maury from the

beginning had said that his observations would be useful for a nautical almanac, the two functions of observing and predicting could be separated.³

One of the first issues that had to be decided related to the question of an American Prime Meridian, a subject already broached during the struggle to establish the Almanac Office. Not only was Davis convinced of the need for an *American Ephemeris* because of his work with the Coast Survey, he also wanted to reference his survey work to an American prime meridian rather than one that lay far away across the ocean. Once raised, the idea was supported by the leading American scientists of the day — Alexander D. Bache, Joseph Henry and Maury himself. But the issue of the establishment and location of an American prime meridian was contentious, and resulted in an interesting and well-documented debate. I will note here only that the issue went all the way to Congress, and the House Committee on Naval Affairs, with all of the debate documentation in hand, recommended to Congress a compromise solution by proposing the adoption of an American prime meridian for astronomy and geography, while retaining the Greenwich meridian for the navigational part of the Almanac.⁴ As a direct result of this decision that the meridian of Greenwich would be used for navigators and the meridian of Washington for astronomers, the *American Ephemeris* had a peculiar bipartite form, one part of more use to astronomers and the other part tailored for navigators. The ephemeris for the meridian of Greenwich gave the ephemerides of the Sun, Moon and planets together with lunar distances. The ephemeris for the meridian of Washington gave the positions of the principal bright stars, the Sun, Moon and larger planets, and other phenomena predicted and observed including eclipses, occultations and motion of Jupiter's satellites. This, of course, would be most useful for observers in the United States.⁵

From the beginning, Davis considered the work of the Nautical Almanac Office broader than publishing rows of useful numbers. Most generally, Davis wished "to advance that which is, and has always been, the principal object of astronomy; and that is, in the language of Bessel, to supply precepts by which the movements of the heavenly bodies, as they appear to us from the earth, can be calculated." This, he considered, was the highest calling of astronomy, much more important than mere descriptive astronomy. It was an activity designed not only to improve the safety of navigation but also to contribute to astronomy, compensating

American mathematicians for their often unsung labors, and proving a credit to the country that supported this highest form of intellectual endeavor. An *Astronomical Ephemeris*, Davis added, "was something more than a book of mere results of calculations based upon rules furnished elsewhere; it should itself help to investigate the theories it is obliged to employ."⁶ This is one of the central themes throughout the history of the Office. As evidence of Davis's commitment to this ideal, already in 1852 the Navy Department published essential sections of Davis's translation of Karl Friedrich Gauss's classic *Theoria Motus Corporum Coelestium* [Theory of the Motion of the Heavenly Bodies Moving about the Sun in Conic Sections, 1857].⁷

While waiting for a resolution of the problem of the meridian to which the almanac would be referred, and for the lunar and solar tables of Peter Hansen that would improve the predicted positions of the Sun and Moon, Davis had four computers begin a new set of tables of the planet Mercury based on the theory of the French astronomer U. J. J. Leverrier. Even using such classical European work in celestial mechanics, one can imagine the problems that Davis faced: "it has been necessary to train the computers for a work such as has never before been undertaken in this country," he wrote. Nevertheless, following his own precept, Davis set about not only producing an Almanac, but also revising theories of the planets on which it was based, including the theory of Neptune that "belongs, by right of precedence, to American science."⁸ By 1852 he had recruited a variety of people, whose rank may be gathered from their pay (Figure 1) and their division of work (Figure 2). Figure 1 also shows how labor intensive Almanac production was. Arriving at Cambridge in 1857, Simon Newcomb entered the happy ambiance of the young Almanac Office that he described in his *Reminiscences*. He took well to the life of a "computer", which paid him \$30 per month.⁹

Already in his *Annual Report* for 1851 Davis boasted of the practical results of the *American Nautical Almanac* — they reduced to one third the average errors of the Moon's place given in the British *Astronomical Ephemeris*. A crucial test was the solar eclipse of 28 July, 1851. According to Davis, the British almanac was 85 seconds in error at Cambridge and the American Almanac 20 seconds; at Washington the British Almanac was in error 78 seconds for beginning of eclipse, 62 seconds for the end, while the American Almanac erred only 13 and 1.5

seconds respectively. Davis pointed out that the French and Berlin almanacs used the same tables as the British, and so were also in error by the same amount. In practical terms this meant 15-20 miles error in determination of longitude at sea by lunar observations.¹⁰

Called upon by a member of the U. S. Senate to defend his work in 1852, Davis appealed to the scientific reputation of the country, "already established and widely extended by the coast survey and the national observatory." And he took the opportunity to summarize the nature of the volume: to embrace all the information necessary to determine at any time the absolute and relative positions of the Sun, Moon and planets, and some of the brightest stars; the phenomena for determination of longitude, including occultations, lunar distances, transits of the Moon and stars, and eclipses of Jupiter; also places of the minor planets, rules and tables for nautical astronomy, tables of tides and geographical position. The geographical extent of the U.S. he argued, "makes it apparent that neither the authorities nor standards of Europe can satisfy our demands."¹¹ The work of the Nautical Almanac Office, Davis concluded, also serves the advancement of science and the diffusion of knowledge in the United States.

In January 1853 the first volumes of a total print run of 1000 copies of *The American Ephemeris and Nautical Almanac* (Washington, 1852), were transmitted to Washington. Undoubtedly in part because of its success, in 1854, after 31 years in the Navy and 23 in the grade of Lieutenant, Davis was promoted to Commander. In November 1856, he accepted a new command, and although Davis would return to head the office from 1859-1861, as the founding Director of the Office, he had placed his indelible stamp on the most creditable American mathematical feat to date. By 1860, supporters of the *American Ephemeris* argued that "Hardly a single civilized nation considers its naval equipment complete without a Nautical Almanac. Six thousand copies of this year are spoken for; ten thousand will soon be the annual sale. The sale is constantly increasing, and the American is fast taking the place of the British Almanac in our own market."¹²

Davis's successor as Superintendent in November 1856 was Joseph Winlock, who except for a brief period in 1859-61 would head the office for a decade, including the Civil War years. As Figure 3 shows, he was the first in a long line of Professors of Mathematics, USN, to head the office.

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In the amount specified as the expenditure for the fiscal year 1851-'52, is included the cost of printing up to the 12th of October, 1852, because it is a part of the regular expenditure for that year.

I have the honor to transmit, also, a statement detailing the current expenses of the office during the present year.

Very respectfully, your obedient servant,

CHARLES HENRY DAVIS,
Lieutenant, Superintendent Nautical Almanac.

Hon. JOHN P. KENNEDY,
Secretary of the Navy, Washington, D. C.

Estimate for the Nautical Almanac for the fiscal year 1853-'54.

For salaries of computers.....	\$16,200 00
For the purchase of paper, printing, &c., in order to publish, in the year 1854, the Nautical Almanac for the year 1857, and for other occasional printing.....	2,200 00
For clerk.....	500 00
For contingent, (including rent, servant hire, &c.).....	500 00
Total.....	<u>19,400 00</u>

The amount of this estimate is the same as that of the preceding year.

Respectfully,

CHARLES HENRY DAVIS,
Lieutenant, Superintendent.

CAMBRIDGE, October 14, 1852.

Detailed estimate of the current expenses of the Nautical Almanac for the fiscal year ending June 30, 1853.

COMPUTERS.

Professor Peirce.....	\$1,500
Professor Shubert.....	1,200
Professor Winlock.....	1,200
J. D. Runkle.....	1,200
Nathan Loomis.....	1,000
John Downs, as computer.....	600
John Downs, as corrector of the press.....	800
J. M. Van Vleck.....	1,000
B. S. Hedrick, as clerk.....	500

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H. Doc. 1.

B. S. Hedrick, as computer.....	\$500
Professor E. O. Kendall.....	900
C. H. Sprague.....	800
J. E. Oliver.....	600
W. C. Kerr.....	600
E. J. Loomis.....	500
J. G. Runkle.....	500
Dr. B. A. Gould.....	500
M. Mitchell.....	500
J. B. Bradford.....	400
C. A. Runkle.....	400
Professor A. W. Smith—off.....	300
J. A. Wilder.....	300
Chauncy Wright.....	300
Charles Hale—off.....	300
E. C. Bache, copyist.....	300
	<hr/>
	16,700
Deduct.....	600
	<hr/>
	16,100

MISCELLANEOUS.

Printing almanac.....	2,150
Occasional printing.....	50
Rent of rooms.....	378
Books.....	50
Stationery.....	150
Fuel.....	127
Servant.....	120
Contingent.....	275
	<hr/>
Total.....	19,400

Very respectfully,

CHARLES HENRY DAVIS,

Lieutenant, Superintendent.

CAMBRIDGE, November 2, 1852.

Fig. 1. (Left and above) Budget estimate for the Nautical Almanac Office for the fiscal year ending June 30, 1853. "Computers" are ranked by salary, which was by far the largest expense item in the total budget.

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H. Doc. 1.

DIVISION OF WORK.

Professor Peirce—The general theory; planets generally; Mars particularly. Mr. J. B. Bradford, assistant.

Professor Winlock—Sun and Mercury, Astraea, Egeria.

Mr. J. D. Runkle—Last ninety-two days of moon, Pallas. Mr. C. A. Runkle, assistant.

Mr. Van Vleck—Second ninety-two days of moon, Hausen's theory of Jupiter and Saturn. Mr. E. Loomis, assistant.

Mr. B. S. Hedrick—First ninety-one days of moon, Metis, Ceres. Mr. W. C. Kerr, assistant.

Mr. C. Wright—Third ninety-one days of moon. Mr. J. G. Runkle, assistant.

Mr. J. E. Oliver—Latitudes and longitudes; miscellaneous.

Mr. John Downs—Occultations, Saturn; proof-reading. Mr. J. A. Wilder, assistant.

Miss M. Mitchell—Venus.

Professor E. Shubert—Iris and other asteroids.

Professor E. O. Kendall—Jupiter and Neptune.

Professor A. W. Smith—Flora.

Mr. C. Hale—Clio.

Dr. B. A. Gould—Vesta, Hygeia.

Mr. C. H. Sprague—Fixed stars.

Mr. Nathan Loomis—Star table.

Mrs. E. C. Bache—Copyist.

I transmit with this report a proof copy of the general preface to the first number of the Nautical Almanac, for the approval of the department.

In conclusion, I have the honor to inform the department that, notwithstanding the slight delays referred to in the beginning of this report, the general state and progress of the work under my charge is satisfactory.

Very respectfully, your obedient servant,

CHARLES HENRY DAVIS,

Lieutenant, Superintendent Nautical Almanac.

HON. JOHN P. KENNEDY,

Secretary of the Navy, Washington, D. C.

Fig. 2. Division of work among Nautical Almanac Office computers in 1852

Superintendents of the Nautical Almanac Office

LT Charles Henry Davis	July 11, 1849 (ordered)—Nov. 23, 1856
Prof. Joseph Winlock	Nov. 23, 1856—August 9/10, 1859
CDR Charles Henry Davis	Aug. 10, 1859—Sept. 18, 1861
Prof. Joseph Winlock	Sept. 18, 1861—May 1, 1866
Prof. John H. C. Coffin	May 1, 1866—Sept. 15, 1877
Prof. Simon Newcomb	Sept. 15, 1877—Sept. 20, 1894

Directors of the Nautical Almanac Office (Title changed Sept. 20, 1894)

Prof. Simon Newcomb	Sept. 20, 1894—Mar. 12, 1897
Prof. William W. Hendrickson	Mar. 12, 1897—June 30, 1897
Prof. William Harkness	June 30, 1897—Dec. 15, 1899
Prof. Henry D. Todd	Dec. 15, 1899—Aug. 24, 1900
Prof. Stimson J. Brown	Aug. 24, 1900—Mar. 25, 1901
Prof. Walter S. Harshman	Mar. 28, 1901—Oct. 1, 1907
Prof. Milton Updegraff	Oct. 1, 1907—Nov. 2, 1910
A. James Robertson	Sept. 18, 1929—May 31, 1939
Walter M. Hamilton	May 31, 1939—Feb. 1, 1940
Wallace J. Eckert	Feb. 1, 1940—Feb. 28, 1945
Gerald M. Clemence	Feb. 28, 1945—Jan. 31, 1958
Edgar W. Woolard	Jan. 31, 1958—Jan. 31, 1963
Raynor L. Duncombe	Jan. 31, 1963—July, 1975
P. Kenneth Seidelmann	Feb. 29, 1976—Sept. 1990

In September 1990 the Astronomical Applications Department was created and the Nautical Almanac Office became a branch of that Department, first under Paul Janiczek (Sept. 1990-July 1997), then under John Bangert (Dec. 1997—present).

Chief, Nautical Almanac Office [under Astronomical Applications Department]

LeRoy E. Doggett	Sept. 1990—April 1996
Alan D. Fiala	April 1996—present

Fig. 3. Superintendents, Directors, and Chiefs of the Nautical Almanac Office

Compared to the battles and fundamental decisions of the Davis period, under Winlock's tenure it was relatively smooth sailing, as the office settled down to the routine annual production of the Almanac volumes. With the end of the Civil War in 1865 and the departure of Winlock and the move to Washington in early July, 1866, the Nautical Almanac Office entered a new era.

Washington, D. C.: Transition and Newcomb Era, 1866-1897

The Newcomb era of the Nautical Almanac Office did not begin immediately upon its move to Washington in 1866. Although Simon Newcomb had worked in the Almanac Office in Cambridge beginning in 1857, in 1861 he had transferred to the Naval Observatory, and was busily advancing his career there. But on Joseph Winlock's departure in 1866 to become Director of Harvard College Observatory, Newcomb must have watched with interest as J. H. C. Coffin was made Superintendent of the Almanac Office. One of Maury's earliest recruits to the Naval Observatory in 1845 as a Professor of Mathematics, Coffin had gone on to head the Department of Mathematics at the Naval Academy in 1855, and upon Chauvenet's retirement in 1860 also became head of the Department of Navigation and Astronomy. There was no question at this juncture of the young Newcomb taking the job that eleven years later he would clearly inherit; at the age of 30 he had only nine years of experience and had not yet made a reputation. Thus it was Coffin who would inherit the work of Davis and Winlock at the Nautical Almanac Office, a work that he shepherded over the next twelve years. By one account, as evidenced in the volumes of the Almanac from 1869-1880, Coffin's influence "although appreciable, cannot be called great. New positions of the standard stars were introduced on more than one occasion and 'changes of detail have from time to time been introduced into the work, but the general plan has remained unaltered.'" ¹³ Coffin's work was reputable, but unremarkable, so one could not speak of "the Coffin Era" in any significant way.

The most remarkable event of Coffin's tenure was not in the Almanac itself, but in the office, which was moved from Cambridge to rented quarters in Washington in July, 1866. The reasons, which had little to do with Coffin, were as compelling as those that had determined the original location in Cambridge. The most original work of Benjamin Peirce was finished, and the following year Peirce would succeed Bache as Superintendent of the Coast Survey in Washington. Davis, the founder

of the Almanac Office, was now head of the Naval Observatory, and he perhaps persuaded the head of the Bureau of Navigation to relocate the Nautical Almanac Office to Washington. Although still not joined with the Naval Observatory, Newcomb undoubtedly took the opportunity of its proximity to visit the office he would one day head.

On Coffin's retirement from the Navy, on September 15, 1877 Simon Newcomb (Figure 4) was named Superintendent of the Nautical Almanac Office. Born in Nova Scotia, in September, 1853, he made his way to a teaching post at a country school at Massey's Cross Roads in Kent County, Maryland, where his father had settled. The following year he moved on to a small school in Sudlersville, Maryland, and finally (in 1856) to a tutoring position some 20 miles from Washington, D.C. During this period Newcomb frequented the library of the Smithsonian Institution, met its Secretary, Joseph Henry by chance in the library, and was recommended to the Coast Survey Office. J. E. Hilgard at the Coast Survey in turn recommended him to Winlock at the Nautical Almanac Office in Cambridge, Massachusetts, where Newcomb arrived in January, 1857. It is remarkable that Newcomb to this point was entirely self-taught in mathematics and astronomy, and although he studied under Benjamin Peirce at the Lawrence Scientific School of Harvard in 1857-1858, he remained largely self-taught throughout his life. Newcomb had obtained his position at the Naval Observatory in October 1861, with the defection of several Professors of Mathematics (as well as Superintendent Matthew Maury) to the Southern cause of the Civil War.

The Nautical Almanac Office at the time Newcomb took charge was "a rather dilapidated old dwelling-house, about half a mile or less from the observatory, in one of those doubtful regions on the border line between a slum and the lowest order of respectability." The permanent occupants of the office were Newcomb, his senior assistant Mr. Loomis, a proof reader and a messenger. All of the computers worked at their homes. One of Newcomb's first steps was to secure a new office at the top of the new Corcoran Building. The change from the Naval Observatory, Newcomb later recalled, was "one of the happiest of my life." He was now in a position of "recognized responsibility", and because he had complete control of the office he could now plan and carry out the research he desired.¹⁴

And this is exactly what he did, to the extent that Newcomb more than any other man dominates the history of the Nautical Almanac Office, and indeed has been called "the most honored American scientist of his

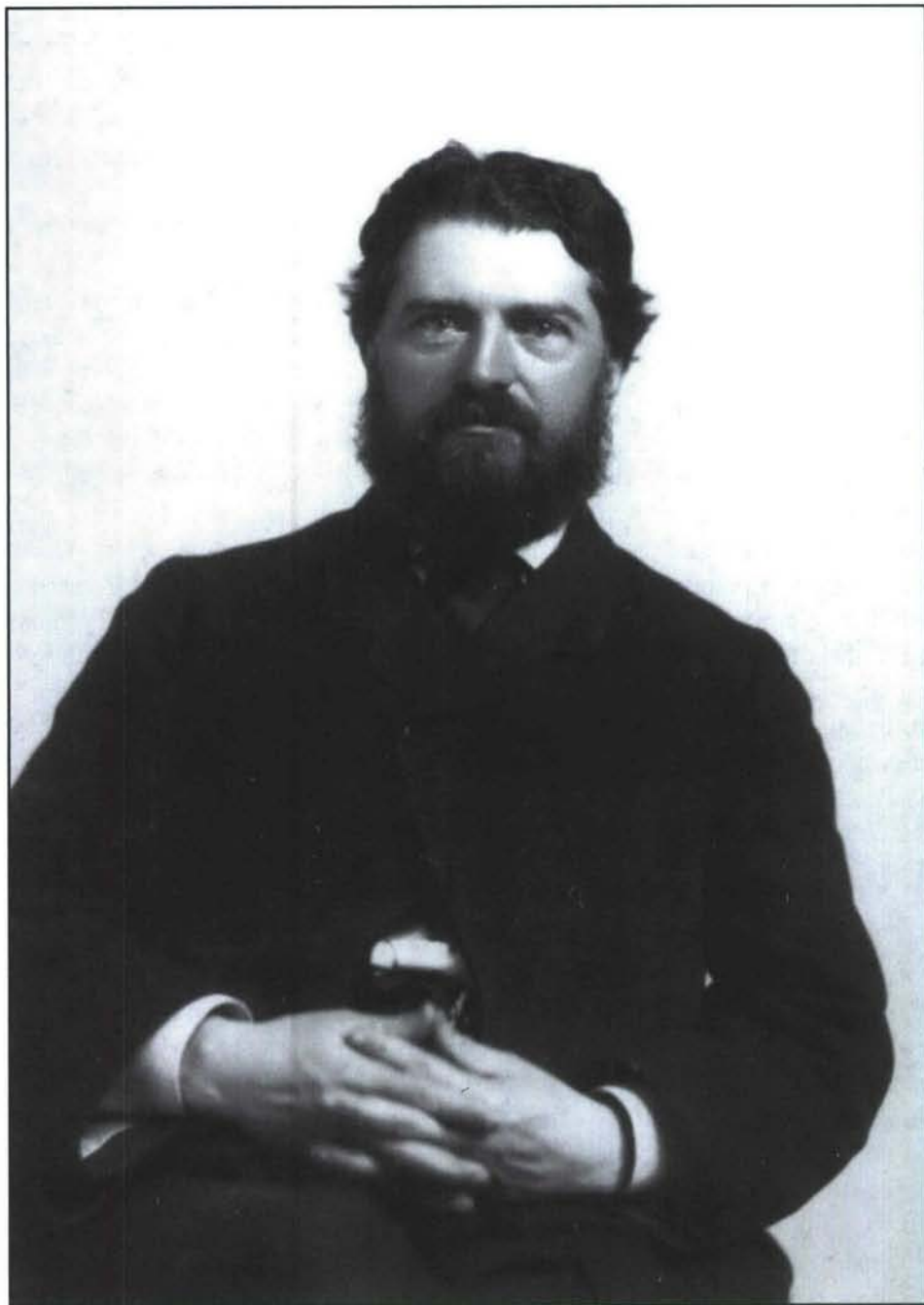


Fig. 4. Simon Newcomb in the 1870s, when he became Superintendent of the Nautical Almanac Office

time,” wielding unparalleled influence on both professional and popular astronomy.¹⁵ Newcomb’s name is associated with his work during the 1860s and 1870s with the transit circle, the transit of Venus and the 26 inch refractor at the Naval Observatory. Newcomb’s career, however, may only be understood in terms of the central driving force of his last 30 years: placing planetary and satellite motions on a completely uniform system, and thereby raising solar system studies and the theory of gravitation to a new level. This could be carried out under government funding because it meant reforming the entire theoretical and computational basis of the American Ephemeris, a goal which he carried out as Superintendent of the Nautical Almanac Office from 1877 to 1897. Thus Newcomb’s seemingly disparate work on the transits of Mercury and Venus, the velocity of light, the constant of nutation, lunar motion and many other subjects may only be understood as part of this grandiose scheme, which encompassed reform of the system of astronomical constants, determinations of the elements of planetary orbits, and the production of tables of motion of the Moon and planets based on the new data. “To endeavour to build up the theory of our whole planetary world on an absolutely homogenous basis of constants was an almost superhuman task,” a fellow European scientist remarked in 1899. “One would have been inclined to predict the failure or, at least, only partial success of such a scheme,” the mathematician G. W. Hill wrote on Newcomb’s death in 1909, “but Professor Newcomb, by his skilful management, came very near to complete success during his lifetime; only tables of the Moon were lacking to the rounding of the plan.”¹⁶ Through sheer perseverance — and a good deal of help from dedicated colleagues like Hill — Newcomb largely succeeded in his life’s goal.

Newcomb’s work traces its lineage to the 18th century continental mathematicians — especially the third volume of the *Mécanique Céleste* of Laplace, who conceived the method of finding algebraic expressions for the positions of the planets at any time, giving their latitude, longitude and radius vector as a function of time. This method required that at least six of the seven elements of each orbit (such as period and orientation of the ellipse) be derived from observation. Even once these elements were determined, no algebraic expression could give a rigorous solution. Instead, the expression was an infinite series of terms; by using more and more of the terms, one could approach mathematical exactness, but never reach it. Even then, no general expression was applicable to all cases, so

that one was needed for the inner planets, one for the Moon, one for Jupiter and Saturn, one for the minor planets, and so on. These expressions were in each case worked out by individual astronomers and mathematicians focusing on one case. Thus Charles Delauney at Paris Observatory and Peter Hansen at Gotha spent significant parts of their careers on the Moon, Lindenau and Alexis Bouvard produced tables lasting through the first half of the 19th century based on Laplace's formulae, and Leverrier undertook the next complete reconstruction of the planets. For the *American Ephemeris* Winlock constructed new tables of Mercury based on the formulae of Leverrier. And in 1872 G. W. Hill constructed new tables for Venus. Old tables, however, were still used for Mars, Jupiter and Saturn. Newcomb's goal, then, was to be able to compute ephemerides from a single uniform and consistent set of data. Just as a single Observatory such as Greenwich adopted consistent methods for observation, Newcomb wished to bring uniformity to the computed positions based on observation. This meant, for example, a uniform set of planetary masses, each determined as accurately as possible, and each used in an adopted best theory.¹⁷

Best known among Newcomb's assistants was George W. Hill (Figure 5), whom Newcomb called "the greatest master of mathematical astronomy during the last quarter of the nineteenth century."¹⁸ Newcomb assigned Hill the most difficult job of all, the theory of motions of Jupiter and Saturn, made difficult because their great masses and relative proximity caused larger perturbations than in the case of the other planets. Ten years later, he produced his results in volume 4 of the *Astronomical Papers of the American Ephemeris*. Newcomb pointed to the "eminently practical character" of Hill's research, in which he concentrated not so much on elegant formulae but rather on the utmost precision in determination of astronomical quantities. The next ten years of his life were spent on correcting the orbits of Jupiter and Saturn and constructing tables of their motion, after which he returned home. "During the fifteen years of our connection," Newcomb wrote, "there was never the slightest dissension or friction between us."¹⁹

For this work Newcomb founded the *Astronomical Papers Prepared for the Use of the American Ephemeris and Nautical Almanac*. In the first volume, published in 1882, Newcomb explicitly stated the purpose of this series of papers as "a systematic determination of the

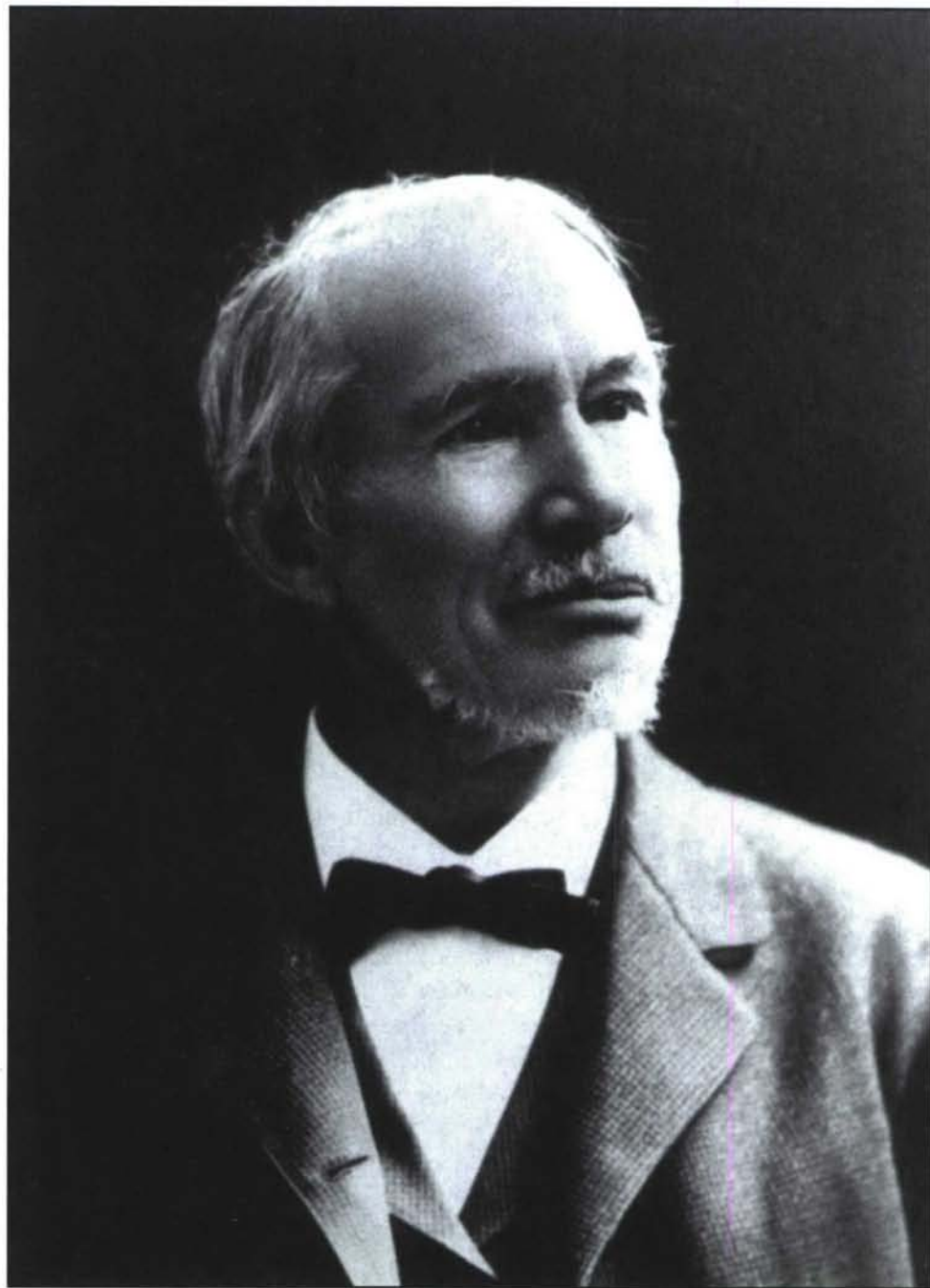


Fig. 5. George W. Hill, master mathematical astronomer, best known for his work on the orbits of Jupiter and Saturn

constants of astronomy from the best existing data, a re-investigation of the theories of the celestial motions, and the preparation of tables, formulae, and precepts for the construction of ephemerides, and for other applications of the results." In the Introduction to this volume, Newcomb made the first published announcement of his program. Even though he had it in mind when taking over the Superintendency of the Office in 1877, only now, when Congress and the Navy Department had supplied all the assistance asked for, including a force of eight to twelve computers, did Newcomb feel confident of carrying the program through. At the same time, he set forth the unpublished work now in progress, the program for its continuance, and called for cooperation of astronomers around the world.²⁰ The first volume, in which four of the six papers were authored by Newcomb himself, demonstrated the variety of topics that would be relevant to Newcomb's program. Newcomb discussed solar eclipses and transit of Mercury observations, compared the theories of the Moon of Hansen and Delaunay, and published his catalogue of 1098 standard reference stars. Albert A. Michelson discussed his experimental determinations of the velocity of light, while G. W. Hill calculated perturbations of Venus on Mercury. By Newcomb's death, 7 volumes had been published, with most of the papers by Newcomb, with results fully justifying W. W. Campbell's characterization of the volumes collectively as one of the great treasures of astronomy.

The patronage of the Navy and the nation for Newcomb's work is in some ways surprising. Not only was the Almanac Office staff greatly increased in order to undertake Newcomb's program, the *Astronomical Papers* were also published by the Navy's Bureau of Navigation. From the outset Newcomb frankly admitted the limited immediate value of his investigations for practical applications. Existing tables of the planets, he wrote, were "not unsatisfactory" for current purposes; with the exception of the Moon, he saw "every reason to suppose that the tabular positions will serve the purposes for which they are immediately required in navigation and practical astronomy." Newcomb, however, was not satisfied with such a narrow victory over Nature, insisting that "when we take a wider view and consider the general wants of science both now and in the future, we find that in the increasing discordance between theory and observation there is a field which greatly needs to be investigated."²¹

Finally, in 1895 Newcomb's preliminary results were published as *The Elements of the Four Inner Planets and the Fundamental Constants of*

Astronomy, completed in 1899 with his publication of the tables of Uranus and Neptune. In the estimation of E. W. Brown at Yale, "this volume gathers together Newcomb's life-work and constitutes his most enduring memorial."²²

In 1896 occurred what Newcomb described as "the most important event in my whole plan", implementing the new system of astronomical constants as determined by Newcomb. David Gill had first suggested in 1894 that a conference be held to stimulate cooperation among the principal almanac offices, and Arthur M. W. Downing, Director of the British Nautical Almanac Office, took the initiative to put together the Paris conference in May 1896. Represented at this meeting were the American, British, German and French Almanac offices. They agreed that beginning in 1901 Newcomb's constants would be used in the national ephemerides. This decision was harshly attacked by prominent American astronomers, including Lewis Boss and Seth C. Chandler, the editor of the prestigious *Astronomical Journal*. The objections were both practical and technical. Some felt that Almanac Offices should not impose new constants on the astronomical community unless that community asked for them.²³

Newcomb's great achievement, in the opinion of the eminent astronomer E. W. Brown (who followed up on Newcomb's work by producing tables of the Moon), was not in purely theoretical mathematical investigations, nor in observational astronomy, but in the combination of the two, the comparison of theory and observation. "He was a master, perhaps as great as any that the world has known," Brown wrote, "in deducing from large masses of observations the results which he needed and which would form a basis for comparison with theory." But, Brown noted, Newcomb was not at home in the purely mathematical side of celestial mechanics, where he produced no new methods for dealing with the motions of solar system bodies.²⁴

*The Nautical Almanac Office and the Naval Observatory:
The Twentieth Century*

Transition Years

The Nautical Almanac Office, according to conventional wisdom, became a part of the Naval Observatory when the former moved from the northwest corner of 19th and Pennsylvania Avenue to Observatory Circle in 1893. Both politics and personalities, however, made the actual case far from straightforward. The Office did indeed move to Observatory Circle on October 20 of that year, but only a year later, on September 20, 1894, did the Secretary of the Navy issue a regulation making the Nautical Almanac Office a "branch" of the Naval Observatory. And even then the Office was only absorbed into the Observatory over a period of years. According to Naval Observatory Superintendent C. H. Davis II, who should have known, "In 1894 the Nautical Almanac Office, on account of the crowded state of the Navy Department building, was accommodated at the new Observatory, which was first occupied in 1893; but the Almanac has remained a distinct organization, having its own director and independent appropriations. It has never been merged with the Observatory and should not be. This point should be distinctly noted."²⁵ One needs to remember here that the son of the founder of the Nautical Almanac Office, as well as the Superintendent of the USNO, is speaking. Indeed one finds in the Observatory's Annual Reports after 1894 that the title transforms from Superintendent to Director of the Nautical Almanac Office. But ambiguity remained as to whether the Office was a Department of the Observatory. We can well imagine that Simon Newcomb, who did not retire until 1897, chafed at becoming a part of the Naval Observatory. It was not only the natural inclination that the Superintendent of an independent institution did not wish to become subsumed under another institution, especially one he had anxiously departed 20 years before. There was also the personal matter that the Astronomical Director at the Naval Observatory was William Harkness, long ago Newcomb's best man at his wedding, but now a bitter enemy thanks to the transit of Venus and other controversies. Harkness (Figure 6) would have been Newcomb's boss at the new site, but one can well imagine that Harkness did not give many orders to Newcomb. Finally, in a Navy Department decision rendered January 19, 1905, the Nautical Almanac Office was held not to be a separate shore station, and this ruling seems to have settled the matter. Writing in 1928, Naval Observatory

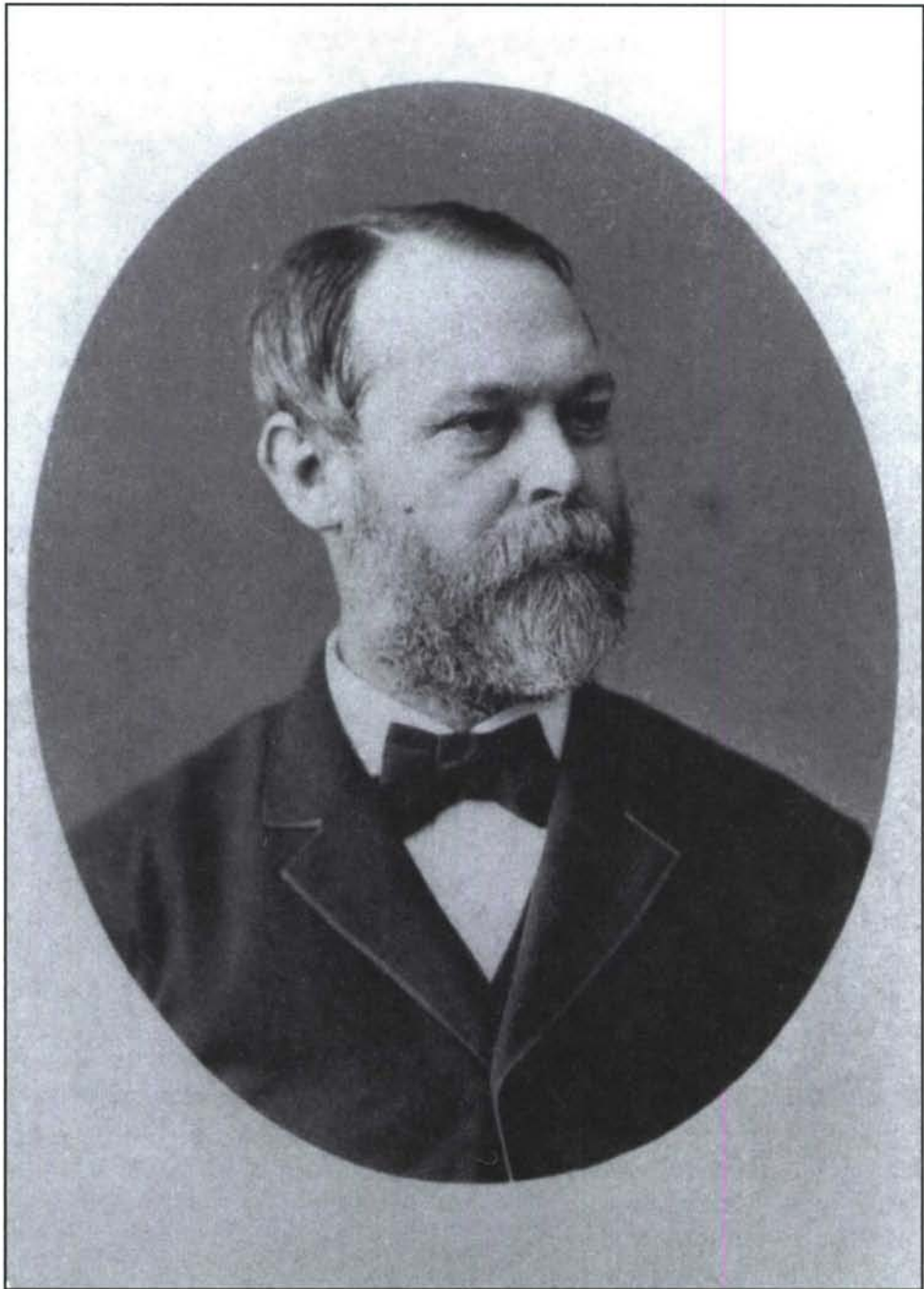


Fig. 6. William Harkness, first Astronomical Director of the U. S. Naval Observatory, and Director of the Nautical Almanac Office, 1897-1899.

Superintendent C. S. Freeman stated that "In 1904, the Nautical Almanac Office, which for 10 years had been located in the observatory grounds under general observatory supervision, was definitely incorporated as an integral part of the observatory organization and has functioned as a department of the organization ever since."²⁶

Not surprisingly, even after his retirement, Newcomb's legacy dominated the Nautical Almanac Office, especially until his death in 1909. After Newcomb's retirement in 1897, the position of Director was held by a succession of four Professors of Mathematics in four years (Figure 3), including Harkness. Ironically, Harkness was left with the task of incorporating Newcomb's constants, as adopted at the Paris Conference in 1896, in the Ephemeris for 1901. He was also left with the ensuing controversy; the new constants, he wrote, "met so much opposition among prominent American astronomers that it has been thought best to give in the Ephemeris for 1901 sufficient data to enable either the constants of Struve and Peters or those of the Paris conference to be used with equal facility, and thus each astronomer is left free to choose for himself which he will employ." This was hardly in the spirit of the intended standardization, and eventually Newcomb's constants won out; beginning with the volume for 1912, only Newcomb's constants were used in the body of the book.²⁷

The Eichelberger and Robertson Years, 1910-1939

Beginning in 1910 two figures dominated the Nautical Almanac Office until World War II, William S. Eichelberger and A. James Robertson. Though their contributions were very different (Eichelberger's scientific and Robertson's political), their tenure saw no radical changes in the Office or its work.

The appointment of William S. Eichelberger as Director in 1910 brought stability back to the Nautical Almanac Office; during a tenure of almost 20 years, Eichelberger earned the respect not only of his colleagues but also of the wider astronomical community, extending to his activities in the nascent International Astronomical Union, where he was President of Commission 4 on Ephemerides in 1925. Eichelberger (Figure 7) had obtained his PhD in astronomy from Johns Hopkins in 1891, and came to the Naval Observatory in 1896. In 1900 he passed the competitive exam to become a Professor of Mathematics (taking the place of Harkness) and



Fig. 7. Walter S. Eichelberger, Director of the Nautical Almanac Office, 1910-1929

advanced to the rank of Captain in 1920. Eichelberger is well-known for his contributions to fundamental meridian astronomy, and especially for his catalogue of *Positions and Proper Motions of 1504 Standard Stars* (1925), adopted as the standard by the IAU in 1925 and used by the national ephemerides until 1940.

Two themes stand out in Eichelberger's tenure: international cooperation and small, but significant, changes to the Almanac. Already at the beginning of Eichelberger's tenure, the issue of international cooperation came to the fore. A program of exchange of data had been recommended at the International Congress in Paris in 1911, and the following year the naval appropriation bill approved by Congress authorized the Secretary of the Navy "to arrange for the exchange of data with such foreign almanac offices as he may from time to time deem desirable, with a view to reducing the amount of duplication of work in preparing the different national nautical and astronomical almanacs and increasing the total data which may be of use to navigators and astronomers available for publication in the American Ephemeris and Nautical Almanac." The United States did have some reservations, however, as evident in a clause stating that the agreement could be terminated on one year's notice. One of the reservations was the use of the Greenwich meridian, which had been used from the beginning for nautical purposes. The Navy wished to reserve the right to use the meridian of Washington for certain ephemerides. On the positive side, however, Eichelberger noted that data exchanges should allow more time to devote to original research. In fact, beginning with the volumes for 1916, the computations were shared by the nautical almanac offices of France, Great Britain, Germany and the United States.²⁸

Changes made to the Almanac during Eichelberger's years were mostly technical or stylistic, but interesting landmarks nonetheless. One of the most noticeable (already a *fait accompli* when Eichelberger took office) was the discontinuation of the lunar distance tables beginning in the *Nautical Almanac* for 1912. Inquiries made in 1907 by the Chief of the Bureau of Equipment, showed that "these tables are practically no longer used by the navigators either of the naval service or of the merchant marine."²⁹ Thus, the chronometer method, which had become the primary method of navigation already by the late 19th century, completely superseded lunar distances. In 1916 Eichelberger initiated another change, tailoring the *Nautical Almanac* to the use of the navigator. The *American*

Ephemeris from its beginning had been divided into two distinct parts. The first part was the ephemeris for the use of navigators, which was reprinted as the *Nautical Almanac*. Since 1916 the *Nautical Almanac* was prepared separately from the *Ephemeris* and therefore designed especially for navigators. The precision required for astronomers was replaced by the lesser precision needed for navigation, and the form and arrangement of the Tables were changed.³⁰ Perhaps the biggest change in content was in the Almanac beginning in 1925, where the civil day beginning at midnight was introduced rather than the day beginning at noon.³¹

With Eichelberger's departure in 1929 a considerable controversy erupted over his successor. Despite many objections from the American astronomical community, that successor would turn out to be A. James Robertson, the Assistant Director of the Office and the first person to assume the Directorship who was not a Professor of Mathematics, USN. Robertson (Figure 8), the son of one of the first settlers of Washington State, had received his B.S. from the University of Michigan in 1891. He became an assistant in the Nautical Almanac Office in 1893, working under Simon Newcomb.³² Perhaps his greatest claim to fame was his work on the fifth satellite of Jupiter. Shortly after entering the NAO, Newcomb gave him E. E. Barnard's observations of this satellite, made at Lick Observatory. Robertson derived the elements of its orbit "by the use of formulae he derived for that purpose."³³ Robertson also computed eclipses and occultation's, and in 1933 was awarded an honorary doctorate by Georgetown University.

For the entire decade before World War II James Robertson served as Director of the Nautical Almanac Office. As his critics had predicted, however, he seems to have contributed little original to the Office. He was a good "computer" and did see to it that the Almanacs were produced on time and with accuracy, but he did little research. As the Superintendent, J. F. Hellweg no doubt appreciated Robertson's political contacts, which were very useful in budget fights. The scientific community, however, remained skeptical to the end; at his death in 1960 at the age of 92, the man who had boasted of his work with Newcomb, worked at the Nautical Almanac Office for 46 years, and served as its Director for a decade, earned no obituary in any scientific journal.



Fig. 8 A. James Robertson, Director of the Nautical Almanac Office,
1929-1939

The Eckert and Clemence Years, 1940-1958

By contrast to the relatively sedate and unprogressive years of Eichelberger and Robertson, World War II set in motion large and irrevocable changes both in production and research. Prior to the Space Age Wallace J. Eckert and Gerald Clemence oversaw these changes, which were driven by advances in automation and the beginnings of the computer revolution. The departure of Robertson on May 31, 1939 left a gap in leadership at a crucial time as war was stirring in Europe. The Directorship was offered to Yale astronomer Dirk Brouwer, who declined because the research possibilities at Yale were better. There was, however, a specific need at the Almanac Office that drove the selection process. The methods of the Almanac Office at this time were antiquated, a later Director of the Office recalled: "slide rules, desk calculators, logarithms, Crelle's multiplication tables, things of that sort were being used in order to produce the American Ephemeris and the Nautical Almanac" (Figure 9). The burgeoning Army Air Corps (later transformed into the U. S. Air Force), required a means of navigation as aircraft range became longer and longer. An Air Almanac was needed, indeed had already been experimented with, but with the current methods it would require a large increase in staff. The solution was to hire, on February 1, 1940, Wallace J. Eckert (1902-1971) to head the Office. Eckert (Figure 10), who obtained his PhD in astronomy from Yale in 1931 under Brown, was one of the pioneers of computing equipment. While a Professor of Celestial Mechanics at Columbia, he had become familiar with the punched-card work of Leslie J. Comrie (1893-1950), the leader of punched-card methods in astronomy and the head of the British Nautical Almanac Office since 1930.³⁴

With this background it was natural that Eckert would revolutionize the American Nautical Almanac production methods just as Comrie had a decade earlier for the British Almanac Office. This is exactly what he did with the introduction of punched-card machines, including an IBM tabulator, summary punch, and sorter for the production of the almanacs (Figure 11).³⁵ The *American Air Almanac* was the first "guinea pig" for the punched-card method. Despite sporadic publications for air navigation through the 1930s, based on the suggestions of P. V. Weems among others, only under Eckert in 1941 did the *American Air Almanac* become a regular publication of the American Nautical Almanac

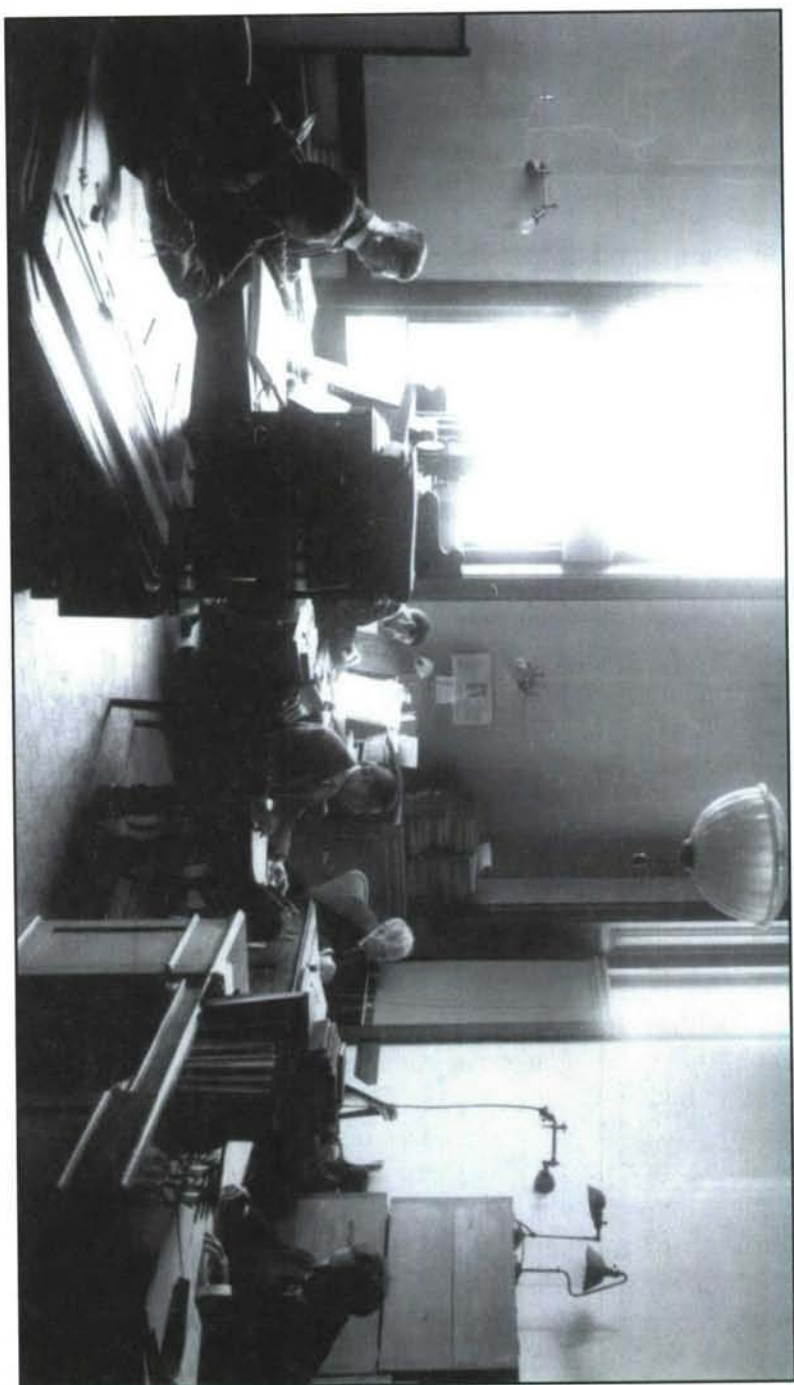


Fig. 9 Nautical Almanac Office personnel, circa 1918, in the days of hand calculators and multiplication tables. The setting is Room W of the Observatory's Main Building. Left to right: Joseph Arnaud, Arthur Snow, Frank Langelotti, Louis Lindsey, James Robertson and Clifford Lewis. Robertson was at this time the Assistant Director of the Office, and was in the room only for the photograph.



Fig. 10 Wallace J. Eckert, Superintendent during the World War II years, introduced punched-card techniques.

Fig. 11. Punched-card machine room, 1941. Helen Smith and Rubye Barnes are running the machines.



Office. Although in the meantime the German (1935), French (1936) and British (1937) Air Almanacs had begun publication, the American Air Almanac was called "the best-constructed Almanac yet devised for the use of navigators".³⁶

The job of automating the preparation of the *American Ephemeris and Nautical Almanac* was led by Paul Herget, an assistant professor of astronomy at the University of Cincinnati who took emergency leave from 1942-1946 in order to help out the Office. As a student at Cincinnati, Herget, like Eckert, had been much affected by Comrie's work on punched-card machines. He would be a pioneer in the application of these machines to astronomical problems. Herget also illustrates how the Office could be pulled to crucial war-time projects using the new techniques. One of the problems was related to heavy Allied submarine losses during the War. By 1943 thirty percent of Allied convoys were being lost to the "wolf pack" tactics of German submarines. Due to fuel shortages, these submarines did not return home immediately after firing their torpedoes, but lay in wait in shipping lanes observing Allied convoys and then radioing to German headquarters the positions of Allied ships. In order to counter this threat, the Allies established more than a hundred listening posts around the world, each keeping constant surveillance for incoming radio messages on a wide spectrum of frequencies. With the solutions of about a quarter million spherical triangles, these observations could locate the submarines within five miles. Because the Nautical Almanac Office had one of the few scientific computation laboratories in the Washington area, in August of 1943, Naval Communications officers visited Eckert and Herget to explain the problem and the possible solution. Herget was assigned the task, assisted only by two "WAVES" from Naval Communications, and the punched-card machinery. They carried out the work 12 hours a day over three months, working at night so that the equipment could be used during the day for the Air Almanac production. By November the book was finished and by December the Allied casualty rate for ships was down to 6%. The computations for the "submarine book", Herget stated, "gave him the greatest satisfaction of his lifetime."³⁷

During the War years Eckert had revolutionized Almanac Office production methods, but as the War neared its end he decided to move on to the Watson Lab. With Eckert's departure in February, 1945, Brouwer was once again offered the position. Brouwer's decline (and the decision of Assistant Director Paul Herget to return to a position at Cincinnati)



Fig. 12. Gerald Clemence, Director of the Nautical Almanac Office, 1945-1958. Clemence also served as the first modern Scientific Director of the U. S. Naval Observatory, 1958-1963.

paved the way for Gerald Clemence (Figure 12) to take over as Director of the Office.³⁸ Clemence had obtained his undergraduate degree in mathematics from Brown University in 1930, and came to the Observatory in the same year. He began as a junior astronomer in the Time Service Division through 1937, then an Assistant astronomer in the 9-inch transit circle Division until 1940, working under H. R. Morgan. In 1940 he joined the Almanac Office, where he worked with Eckert and Herget in introducing the new punched-card machines.³⁹ Clemence's interests went far beyond the routine tasks of Almanac production, tasks that had dominated the office since Newcomb and that War had imposed on Eckert. Clemence was especially interested in the comparison of theory and observations of planetary motions, permitting improvement of the astronomical constants or the planetary theories themselves.⁴⁰

The hallmark of the Clemence era was thus a return to research on the theories of planetary motion. It is not too much to say that Clemence picked up where Newcomb and Hill left off, employing not only a half century of new observations, but also the vastly improved methods, first punched-card and then computer. Already in 1943 Clemence had compared thousands of observations of Mercury from 1765 to 1937 with Newcomb's orbit in order to derive new elements, research published in the same *Astronomical Papers* series where Newcomb's work had appeared.⁴¹ He then tackled the motion of Mars, Newcomb's last and most inadequate planetary project. Finding it needed a complete overhaul, Clemence started from scratch. By 1949 he had published a first-order theory, with the calculations undertaken entirely using punched cards, but he spent 20 years completing the final theory. In 1975, after extensive comparison with observations, Herget characterized the Mars theory as "the most accurate of the general theories for any of the principal planets."⁴² In order to compare theory with observation Clemence had to grapple with the problems of time introduced by the variable rotation of the Earth; in this connection the concept of Ephemeris Time became an issue in which he took the lead.

Though much of Clemence's work was undertaken alone, he also had the benefit of a strong collaboration with Dirk Brouwer of Yale, Eckert at the Watson Scientific Computing Laboratory, and Herget in Cincinnati. This collaboration was greatly strengthened in 1947 when the Office of Naval Research (ONR) awarded a long-term contract to Yale, the Naval Observatory and the IBM Watson Laboratory to undertake work

on a variety of solar system problems. The rationale behind the work was that more accurate theories and tables could be produced in light of the new computing machinery. The ONR contract, which set the research agenda of the Office for more than a decade, centered on a revision of the motions of the principal planets, including Mars. More specifically, the program consisted of six parts: measurement of photographic plates of Saturn's satellites in order to evaluate the mass of the system; improvement of the theory of Jupiter's Galilean satellites; work on the secular perturbations of Pluto; work on the theory of motion of Jupiter and Saturn to see if the theories of motion of the principal planets can be developed with the same degree of accuracy as the lunar theory; accurate orbits of the first four asteroids; and the theory of the motion of Mars by Hansen's method. One of the first products of this collaboration was *Coordinates of the Five Outer Planets, 1653-2060*, which quickly became the standard source for all research and published ephemerides involving the planets from Jupiter to Pluto. Between 1949 and 1970, some 22 papers were published in the *Astronomical Papers* as a result of this collaboration.⁴³

An important aspect to the improvement of theories of planetary motion was the determination of a self-consistent and accurate set of astronomical constants, since the accuracy of all reduction computations for celestial positions depends on the accuracy of values of the astronomical constants used. The introduction of new constants, was, however, a delicate task, as Newcomb had discovered 50 years earlier. While some saw the current system as not completely satisfactory either from the point of view of accuracy or consistency, the practical problem was keeping the amount of recalculation in ephemerides, and in comparison of theory with observation, to a minimum. The problems and potentials of new constants were argued at a seminal meeting in Paris in the Spring of 1950. So controversial was the issue, that only well into the Space Age would new constants be introduced. Improvements to planetary orbits and astronomical constants remained important themes of under the Directorships of Ray Duncombe and P. Kenneth Seidelmann. In 1964 the IAU adopted what was known as the "1968 IAU System of Astronomical Constants". Astronomical theory and practice were advancing so fast, however, that by 1970 it was recognized that the ephemerides in national almanacs required improvements, not only in constants, but also in the fundamental star catalog, the definition of time, and even required the replacement of the B1950.0 epoch for the celestial

reference system. By international agreement, not until the 1984 editions were all these changes, including a new "1976 IAU System of Astronomical Constants", introduced at one time into the national almanacs. In the end Newcomb's constants, and his theories and tables for the Sun and the inner planets, were not completely superseded until 1984.⁴⁴

A final hallmark of the Clemence, Duncombe and Seidelmann years is international collaboration. For years Clemence worked with his British counterpart Donald Sadler to unify the preparation of the British and American nautical almanacs.⁴⁵ As of 1960 the contents of the *American Ephemeris* and of the British *Nautical Almanac* were unified, in accordance with resolutions of the IAU.⁴⁶ In 1961 an *Explanatory Supplement to the Astronomical Ephemeris and The American Ephemeris and Nautical Almanac* was also produced; Seidelmann edited a new and completely rewritten *Explanatory Supplement to the Astronomical Almanac*, published in 1992. Most members of the staff of the American Almanac Office in 1966 are shown in Figure 13.

The Space Age

The beginnings of the Space Age brought the immediate realization that techniques that astronomers had long applied to celestial bodies would now be applied to artificial satellites. The first impact of the Space Age on the Naval Observatory was in the computation of orbits, long the purview of the Nautical Almanac Offices of the world, but now a matter of urgent national concern. The Vanguard project was a Naval Research Lab project, but Clemence and Duncombe served as consultants from the Naval Observatory to that project, where Herget was the principal consultant for orbital computations. By the time the Sputniks went up, Duncombe was loaned almost 100 % of the time to the Vanguard project.⁴⁷ More generally, the Nautical Almanac Office as the Space Age proceeded "met increasing demands for astronomical data and ephemerides arising from space age requirements of other government agencies and industry."⁴⁸ In this, however, they were joined by new players; highly accurate ephemerides of the planets and satellites, critical for space missions, were supplied largely by the Jet Propulsion Laboratory (JPL). The Naval Observatory was slow to adopt new precise observing techniques applicable to ephemerides — radar ranging, Very Long



Fig. 13. Nautical Almanac Office staff, summer, 1966. Front row (left to right): Ralph Haupt, Cdr. Stanfill (Deputy Superintendent), Captain McDowell (Superintendent), Raynor Duncombe, Kaj Strand (Scientific Director), Ruth Meyers. Second row: Jean Hampton, Doug O'Handley, Barbara McMorris, Armstrong Thomas, Berenice Morrison. Third row: Alan Fiala, Sol Elvove, Gertrude Johnson, Vivian Holland, Louise Weston, Louise Long, Victoria Meiller. Back row: Ken Seidelmann, Garold Larson, Dan Pascu, Harry Heckathorn III, Lawrence Buc, William Klepczynski, Peter Schultz, George Brown, Diana Simmons, Judy Wise, Joan Bixby.

Baseline Interferometry (VLBI), Lunar Laser Ranging, spacecraft ranging and Doppler — and the expertise was built elsewhere, including at JPL, MIT and Goddard Spaceflight Center.

Another trend of the Space Age was the increasing use of electronic computers. Because of its need for computing power, the Almanac Office and its descendants were responsible for computers. An IBM 650 was delivered to the Observatory in July, 1957 and fully operational in August, shortly before the launch of Sputnik. Clemence also played a leading role in transitioning the staff to the new methods. Given this impetus, most of the calculations of the Nautical Almanac Office had been programmed for the 650 by 1958, and other parts of the Observatory were soon to follow.⁴⁹ The last IBM 650 was manufactured in 1962, the same year that the Observatory moved on to the next model, the IBM 1410. By 1966 it had acquired an IBM 360 (model 40), and in March 1980 a 4341 replaced the 360. By 1990 the Observatory was engaged in moving all applications off of its two central computers, (an IBM 4381 and a Dec VAX 8530) onto Unix work stations within each Department. And by 1994 the computer support functions were assumed by a new Information Technology Department.⁵⁰

Ironically, a longer-term trend of the Space Age — the use of satellites in Earth orbit as an aid to navigation on Earth — changed navigation radically, and with it the Nautical Almanac Office. With the widespread success and adoption of the Global Positioning System of satellites in the 1990s, celestial navigation became a secondary system. Increasingly navigation depended on the time service, earth rotation, and positional astronomy, all long-standing aspects of work at the Naval Observatory. In 1990 the Nautical Almanac Office underwent a major change “to respond to emerging, specialized needs of the Department of Defence (DoD), the civilian departments of the U. S. government, and the astronomical community for astronomical data.” The result was the formation of the Astronomical Application Department (of which the Nautical Almanac Office was a Division), and the Orbital Mechanics Department. The Astronomical Applications Department retained the Almanac production duties and designed new software products, while the Orbital Mechanics Department continued the research function “to develop accurate planetary, lunar and satellite ephemerides and theories, to provide expertise in celestial mechanics and solar system astrometry.”

By 1995 much of the research function had been subsumed back under the Astronomical Applications Department.⁵¹

In closing, I must emphasize once again that I have only touched the tip of the iceberg in this brief overview. The history of planetary theories, of ephemerides, of astronomical constants, the contributions of numerous scientists not even mentioned here, the international cooperative efforts in the service of accurate navigation, all deserve further research. The history of the American Nautical Almanac Office needs to be seen in the context of the work of the Almanac Offices of the world, especially Her Majesty's Nautical Almanac Office in Great Britain. While many of those offices are older, perhaps none are so closely intertwined with the emergence of science in their respective countries. Few American scientific institutions can boast the 150 years of uninterrupted work that we now celebrate. The American Nautical Office is therefore an important part of the history of science in the United States.

This paper is dedicated to the memory of LeRoy Doggett (Figure 14), friend, colleague, and Head of the Nautical Almanac Office from 1990 to 1996. He exemplifies the hard work and dedication of his colleagues in the Almanac offices of the world over many years, so that navigation and science might move forward.



Fig. 14. LeRoy Doggett, Chief of the Nautical Almanac Office, 1990-1996

NOTES

1 John Y. Mason, *Report of the Secretary of the Navy*, Nov. 25, 1844, 520, and Dec. 5, 1846, 385; Matthew F. Maury, in *Report of the Secretary of the Navy*, October 20, 1845, 690-91. Craig B. Waff, "Navigation vs. Astronomy: Defining a Role for an American Nautical Almanac" (this volume), provides the most complete account, with full citations, of the events leading to the founding of the American Nautical Almanac Office.

2 *Statutes at Large*, 9, 374-375, as cited in Gustavus A. Weber, *The Naval Observatory: Its History, Activities and Organization* (Johns Hopkins Press: Baltimore, 1926), 27. The remainder of the clause reads, somewhat ungrammatically, "that the Secretary of the Navy may when, in his opinion, the interests of navigation would be promoted thereby, cause any nautical work that may, from time to time, be published by the hydrographical office, to be sold at cost, and the proceeds arising therefrom to be placed in the treasury of the United States."

3 Already in an 1847 letter to John Quincy Adams, Maury had conceded that he himself would be unable to superintend the production of a nautical almanac in detail, and advocated a "special and subordinate Superintendent, whose duties should be confined to the details of the work and nothing else." The word "subordinate" implied that Maury wished to maintain overall control, but he did not. Maury to Adams, 17 November, 1848, published in *The Southern Literary Messenger*, January, 1848, pp. 4-10; see also Waff (reference 1 above). Simon Newcomb, *Reminiscences of an Astronomer* (Boston and New York, 1903), 62, states that the Nautical Almanac Office was founded at Cambridge to "have the technical knowledge of experts," especially Peirce; see also C. H. Davis [Jr.], "Memoir of Charles Henry Davis, 1807-1877" *Biographical Memoirs of the National Academy of Science*, 4 (1902), 25-55; C. H. Davis [Jr.], *Life of Charles Henry Davis, Rear Admiral* (Boston and New York, 1899), 74-93.

4 "American Prime Meridian", Report No. 286 to accompany Joint Resolution No. 17, House of Representatives, 31st Congress, 1st session, May 2, 1850, 1-2. On Maury's support for a Washington meridian as early as 1847, see Waff (reference 1 above). On the distinction between

an ephemeris and an almanac, see Alan Fiala, ““Evolution of the Products of the Nautical Almanac Office” (this volume).

5 Newcomb comments on this bipartite form in “The Astronomical Ephemeris and Nautical Almanac,” in *Sidelights on Astronomy* (Harper and Brothers: New York and London, 1906), 191-215.

6 Lt. C. H. Davis, “On the Nautical Almanac,” *Proceedings of the American Association for the Advancement of Science*, fourth meeting held in New Haven, Ct., August, 1850 (Washington, 1851), 56-60.

7 Karl Friedrich Gauss, *Theory of the Motion of the Heavenly Bodies Moving about the Sun in Conic Sections*, A Translation of *Theoria Motus Corporum Coelestium*, by Charles Henry Davis (New York, 1857; reprinted by Dover, New York, 1963).

8 Davis to William Ballard Preston, *Report of the Secretary of the Navy*, Oct 2, 1849, 443-444.

9 Newcomb’s *Reminiscences* (reference 3 above) describes the Office during its early years in the chapter “The World of Sweetness and Light”. Also, Newcomb, “Aspects of American Astronomy,” in *Sidelights on Astronomy*, 290-1 describes the atmosphere of the office under Davis. See also Davis’s reports in *Report of the Secretary of the Navy*, Oct. 12, 1850, 229-230; November 29, 1851, 73-76; and December 4, 1852, 345-348. Figures 1 and 2 are from the latter. Davis summarized the goals of his work at the fourth meeting of the American Association for the Advancement of Science in 1850 (see reference 6).

10 C. H. Davis, in *Report of the Secretary of the Navy*, November 29, 1851, 75.

11 Senate Documents, Ex. No. 78 (1852), reprinted in “Davis’s Report on the Nautical Almanac,” *The American Journal of Science and Arts*,” second series, 14 (Nov., 1852), 335.

12 “Memorandum Concerning the Objects and Construction of a Nautical Almanac,” 11-12, and “Memorandum on the American Ephemeris and Nautical Almanac, showing its special and peculiar merit and Utility,” in *Two Memoranda on the Objects and Construction of the American Ephemeris and Nautical Almanac* (Cambridge, 1860).

13 George C. Comstock, "John Huntington Crane Coffin," *Biographical Memoirs of the National Academy of Sciences*, vol. 8, p. 6.

14 Newcomb, *Reminiscences*, 214. On the early locations of the Nautical Almanac Office in Washington, see Weber (reference 2 above), 27. According to Weber, the Office was first located in rented quarters, before moving to the State, War and Navy Building (now the Old Executive Office Building, next to the White House) in 1883. See reference 25 below for later moves.

15 The best recent studies of Newcomb are Albert E. Moyer, *A Scientist's Voice in American Culture: Simon Newcomb and the Rhetoric of Scientific Method* (Berkeley, 1992), and Arthur Norberg, *Simon Newcomb and Nineteenth Century Positional Astronomy* (PhD Dissertation, University of Wisconsin-Madison, 1974). See also Brian Marsden, "Newcomb," *Dictionary of Scientific Biography*, vol. 10, 33-36.

16 Loewy, "Simon Newcomb," *Nature*, 60 (May 4, 1899), 1-3; George W. Hill, "Professor Simon Newcomb as an Astronomer," *Science*, Sept. 17, 1909, 353-357.

17 Newcomb, "The Astronomical Ephemeris and Nautical Almanac," in *Sidelights on Astronomy* (*op. cit.*, reference 5), 191-215.

18 *Reminiscences*, 219.

19 G. W. Hill, "Tables of Jupiter", *Astronomical Papers of the American Ephemeris*, VII, pt. 1 (1895); Newcomb, *Reminiscences*, 222.

20 Newcomb, *Astronomical Papers of the American Ephemeris* (hereafter APAE), I (Washington, 1882), Prefatory Note, Introduction, x-xi.

21 Newcomb, APAE, I, Introduction.

22 E. W. Brown, "Simon Newcomb," *Bulletin of the American Mathematical Society*, 16 (1910), 341-55: 347.

23 This controversy has been described in Arthur L. Norberg, *Simon Newcomb* (*op. cit.*, reference 15 above), 328-402, and Norberg, "Simon Newcomb's Role in the Astronomical Revolution of the Early Nineteen

Hundreds,” in *Sky with Ocean Joined*, Steven J. Dick and LeRoy Doggett, eds. (Washington, 1983), 75-88.

24 Brown, (*op. cit.*, Ref. 22 above) 353.

25 [C. H. Davis, II], “Memorandum”, U. S. Naval Observatory [USNO] archives, Davis to Colby Chester folder, page 2. From internal evidence the author of the document is certainly C. H. Davis, II, and the date around November 1, 1902, when Chester assumed the Superintendency. On the location of the Almanac Office prior to its removal to Observatory circle see Weber (note 2 above), 27. It had actually been removed from the State, War and Navy Building to the Navy Yard in December, 1889, and to rented quarters at 1901 Pennsylvania Avenue in 1890. Weber gives the date of the Almanac Office move to Observatory Circle as October 20, 1893 (p. 27). See also C. B. Watts, “C. B. Watts Recording his Recollections of the Naval Observatory,” USNO archives.

26 C. S. Freeman, Annual Report of the Naval Observatory for the Fiscal Year 1928, 22; Weber (*op. cit.*, reference 2), 28.

27 William Harkness, in *Report of the Superintendent of the United States Naval Observatory for the Fiscal Year ending June 30, 1898*, 13. Other changes to the volumes during these years are enumerated in the *Annual Report* for 1899, 19-20. On the 1912 date, see the *Annual Report* for 1908, 14.

28 *Annual Report* for 1912, 12-14. Changes in the Almanacs are also discussed in Edgar W. Woolard, “The Centennial of the American Nautical Almanac Office,” *Sky and Telescope* (December, 1951), 27-29..

29 Milton Updegraff, “Preface,” in *The American Ephemeris and Nautical Almanac*, November, 1909

30 Woolard (reference 28), 27-28. Woolard also noted that the Greenwich hour angle was added to the ephemeris of the Moon in 1932, and to the ephemerides of the Sun, planets and stars in 1934. No further changes were implemented until 1950.

31 *Annual Report* for 1923, 12. The evolution of national Almanacs is discussed in P. K. Seidelmann, P. M. Janiczek and R. F. Haupt, “The Almanacs — Yesterday, Today and Tomorrow,” *Navigation: Journal of*

the Institute of Navigation, 24 (1976-1977), 303-312; see also Alan Fiala's, "Evolution of the Products of the Nautical Almanac Office," this volume.

32 Robertson recalled his first meeting with Newcomb, whose office was located in Room 566 of the State, War and Navy Building, while his staff labored two blocks away at 19th and Pennsylvania Avenue. See James Robertson, "Highlights in the Career of Simon Newcomb," *Popular Astronomy*, 44 (November, 1936), 471-475; and Robertson "Recollections of Simon Newcomb," *Journal of the Royal Astronomical Society of Canada*, 30 (Dec, 1936), 419-421.

33 Robertson enumerated his accomplishments, including the Jupiter work, in the "Memorandum for Dr. L. M. Lucas," Dec 30, 1936, USNO archives, Robertson folder. A synopsis of the Jupiter work is *Astronomical Journal*, 35, no. 840, Aug 28, 1934.

34 S. Dick Interview with Ray Duncombe, USNO Library. On Eckert see Henry S. Tropp, "Eckert", in *Dictionary of Scientific Biography*, and M. Gutzwiller's paper in this volume.

35 Wallace Eckert, "Punched Card Methods in Scientific Computation," (Thomas J. Watson Scientific Computing Bureau, 1940).

36 *Annual Report* for 1940, 9; W. J. Eckert, "Air Almanacs," *Sky and Telescope*, November, 1944; and Seidelmann et al (reference 33 above), 307-308. *The American Air Almanac* was renamed *The Air Almanac* in 1953.

37 Donald Osterbrock and P. K. Seidelmann, "Paul Herget", *Biographical Notices of the National Academy of Sciences*, 66. On the submarine work, see Herget, "The Submarine Book" June, 1977, Herget file, USNO Archives, and the "Final Coordinates Tracking Charts HO-5405 ... Series," also in the USNO archives.

38 After Eckert's resignation in March 1945 he was "succeeded by G. M. Clemence, Paul Herget becoming assistant director." In March, 1946 Herget "terminated his leave of absence from the University of Cincinnati . . . when he resigned as Assistant Director of the Nautical Almanac Office to assume active direction of the Cincinnati Observatory." Woolard became Assistant Director. *Annual Report* for 1944-45, in *Astronomical*

Journal., 51 (1946), 214, and *Annual Report* for 1945-46 in *Astronomical Journal*, 52 (1947), 142.

39 On Clemence see Paul Herget, "The Keeper of Mars," *Sky and Tel*, (April, 1975), 215-216; Clemence, "How to Get Medals", USNO archives, Clemence folder. The latter constitutes a brief but interesting autobiography.

40 Gerald Clemence, "On the System of Astronomical Constants," *Astronomical Journal*, 53 (May, 1948), 169-179.

41 Clemence, *The Motion of Mercury, 1765-1937*, APAE, XI, pt. 1 (1943); *Astronomical Journal*, 50 (1943), 126-127; "The Motion of Mercury," *Sky and Telescope* (Dec, 1947), 7, 31-33.

42 Clemence, "First-Order Theory of Mars," APAE, XI, pt. 2 (1949); *Theory of Mars (Completion)*, APAE, XVI, pt. 2 (1961).; Paul Herget, "The Keeper of Mars," *Sky and Telescope* (April, 1975), 215-216.

43 W. J. Eckert, Dirk Brouwer and G. M. Clemence, *Coordinates of the Five Outer Planets, 1653-2060*, APAE, 12 (1951); Dorrit Hoffleit, "Yale and USNO Cooperation Especially in the Brouwer and Clemence Era," *Comments on Astrophysics*, 16 (1992), 17-30: 23-24. On the close personal relationship of the three authors, see Paul Herget, "The Keeper of Mars," *Sky and Telescope*, (April, 1975), 216. The first report on the ONR work is in the *Annual Report*, in *Astronomical Journal*, 53 (1948), 151.

44 IAU *Transactions*, 1968; P. K. Seidelmann, ed., *Explanatory Supplement to the Astronomical Almanac* (Mill Valley, Ca., 1992), 317 ff.

45 G. Clemence and D. Sadler, "The Conformity of the American Ephemeris and the (British) Nautical Almanac," *Observatory*, 75 (1955), 176; "Unification of the Abridged Nautical Almanac and the American Nautical Almanac," *Journal of the Institute of Navigation*, 9, 171-176; "Unification of Astronomical and Navigational Ephemerides," *ICSU Review*, 2 (1960), 1-5.

46 *Annual Report*, in *Astronomical Journal*, 62 (1957), 313.

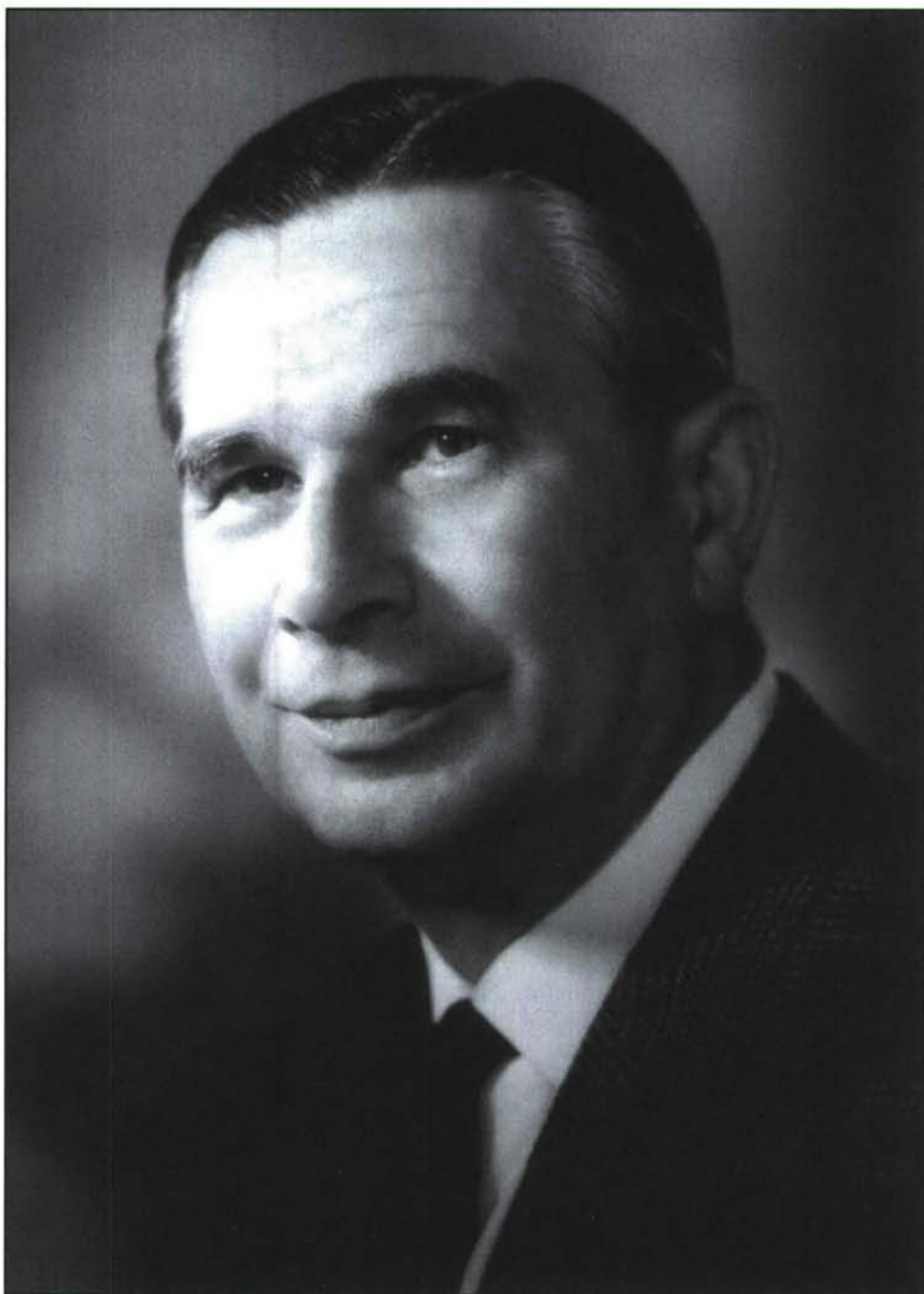
47 *Ibid.*, 312; Duncombe interview, 18, 32-34. Constance Green and Milton Lomask, *Vanguard: A History* (Washington, 1971), especially Ch. 9, "The Tracking Systems," 145-182: 159-161.

48 Annual Report, in *Astronomical Journal*, 65 (1960), 3.

49 *Annual Report*, 1957, 313; *Annual Report*, 1958, 379; Astronomical Council minutes, 1956-57, USNO archives; Charles Bashe, Lyle Johnson et al., *IBM's Early Computers* (Cambridge, Mass., 1986), 165-172.

50 Annual Report, *Bulletin of the American Astronomical Society*, 27 (1995), 661.

51 Annual Report, *Bulletin of the American Astronomical Society*, 24 (1992), 589-590.



Donald H. Sadler
Superintendent, H. M. Nautical Almanac Office, 1937-1970

THE HISTORY OF H.M. NAUTICAL ALMANAC OFFICE

George A. Wilkins

Superintendent of H.M. Nautical Almanac Office, 1970-1989

Summary

The British Nautical Almanac Office was established in 1832 as a replacement for the system of home-based computers and comparers that had been used for the production of the *Nautical Almanac* from 1767 onwards. For the next 100 years the Superintendents of the Office, W. S. Stratford, J. R. Hind, A. M. W. Downing and P. H. Cowell, were content to make only occasional improvements to the Almanac. Then L. J. Comrie and his successor, D. H. Sadler, greatly extended the work of the Office by producing additional publications for astronomy, navigation and computing. The Office also acted as an international centre for occultations of stars by the Moon.

The Office joined other departments of the Royal Greenwich Observatory (RGO) at Herstmonceux Castle, Sussex, in 1949. Very strong links with the Nautical Almanac Office of the U. S. Naval Observatory were developed and arrangements were introduced to share the computation and printing of the almanacs and other publications. From 1975 onwards, however, the staff and activities of the U.K. Office were reduced as the role of the RGO was changed.

Prologue

The international bestseller *Longitude* by Dava Sobel¹ claims to be "the true story of a lone genius who solved the greatest scientific problem of his time", but it fails to give a fair account of the way in which the problem of the determination of longitude at sea was also solved by astronomers.

John Harrison, the hero of Dava Sobel's story, solved the problem by making a mechanical chronometer that would keep time at sea to better than two seconds per month, but such chronometers were extremely expensive and did not come into widespread use for another century.

The development of the alternative astronomical method of 'lunar distances' required the efforts of many persons over many years. The founding of the Royal Observatory at Greenwich in 1675 and the subsequent observations by Flamsteed, Halley and Bradley, provided the

observational basis for the production by the fifth Astronomer Royal, Nevil Maskelyne, of the first edition of *The Nautical Almanac and Astronomical Ephemeris* for the year 1767².

The Almanac contained predicted values of 'lunar distances', that is of the angles between bright stars and the Moon, for comparison with the angles measured by the navigator using a good Hadley's quadrant, or preferably a sextant. It also contained the data that the navigator needed for determining local solar time from observations of the angular elevation (or altitude) of the Sun above the horizon. The navigator also needed a set of *Requisite Tables*, which gave *Instructions for Finding the Longitude at Sea, by the Help of the Ephemeris*, and 'a watch than can be depended upon for keeping the time within a minute for six hours'.

Extracts from the first Almanac and an account of the use of the method of lunar distances are given in a special article³ in the *Nautical Almanac* for 1967. Further information is given in a booklet⁴ and a paper⁵ which were prepared at the time of the bicentenary of the issue of the first *Nautical Almanac*.

Maskelyne continued to be responsible for the production of the *Nautical Almanac* until his death in 1811, when he was succeeded as Astronomer Royal by John Pond. Unfortunately, Pond failed to exercise proper control over the work of preparing the Almanac, and so Thomas Young⁶ was made *Superintendent of the Nautical Almanac* in 1818 at the same time as he was made Secretary of the Board of Longitude. It seems surprising that the Almanacs continue to indicate that they were to be printed according to the directions of John Pond.

Young restored the reliability of the Almanac for navigation, but he had made no attempt to make the Almanac more suitable for use by astronomers⁷. When he died in 1829 the task of supervision reverted to Pond until 1831 when Lt. W. S. Stratford⁸ was appointed Superintendent. Stratford was then the secretary of the Astronomical Society of London (later the Royal Astronomical Society), which had put forward a series of recommendations for changes to the Almanac⁹.

At that time the computations for the Almanac were carried out by persons who worked at home. Each table was calculated independently by two persons and their results were compared by a third person. This system often involved long delays in resolving the discrepancies that occurred. Stratford decided to change this system and set up the *Nautical Almanac Office* in 1832¹⁰.

The first 'century' of the Nautical Almanac Office, 1832-1930

Stratford immediately went to work to implement the recommendations of the Astronomical Society and he introduced many changes into the Almanac for 1834, in which the recommendations were re-printed. One change was the use of Greenwich mean time, rather than apparent time at Greenwich as the argument of the ephemerides. This change recognised the widespread use of mean time by astronomers and the growing use of chronometers for navigation. Nevertheless, many ships continued to rely on the much cheaper method of lunar distances.

For nearly the next 100 years the work of the Office and the Almanac itself gradually evolved without any major changes. Ephemerides of minor planets and comets were soon introduced and later in the century tabulations of the apparent places of stars expanded as they were needed for the accurate determination of time for civil purposes.

Stratford was succeeded in 1853 by John R. Hind¹¹ who had discovered 10 minor planets. He continued to be the director of a private observatory and was active in the affairs of the Royal Astronomical Society. Hind was Superintendent for 38 years and was followed in 1891 by Arthur M. W. Downing¹², an Irishman who had previously worked at the Royal Observatory.

Under Downing the first part of the Almanac, which contained the data for navigational purposes, was published separately from 1896 onwards. A few years later Downing introduced into the Almanac for 1901 onwards ephemerides based on Simon Newcomb's tables and constants, but without first consulting the Royal Astronomical Society. He was criticised, but his decision was upheld.

The prefix H.M. to the name of the Office first appeared without comment in 1904 in the preface to the Almanac for 1907. We have been unable to find the authority for this change, but neither have we found any objection to it.

Philip H. Cowell¹³, who succeeded Downing in 1910, had also previously served in the Royal Observatory and had carried out research on the motion of the Moon. He is, however, now best known for the method of numerical integration that is derived from the method used by Cowell and Crommelin¹⁴ for their accurate computation of the orbit of Comet Halley before its return in 1910. He was frustrated by the refusal by the Admiralty of his request for additional staff for research in celestial mechanics and by his failure to obtain a professorship at

Cambridge.

From then on Cowell was content to oversee the day-to-day work of the Office, and he made no further attempt to continue, for example, his studies of the motion of the Moon. I do not know to what extent he was responsible for the introduction in 1914 of *The Nautical Almanac, Abridged for the use of seamen*.

The work of the Office attracted the attention of a New Zealander, Leslie John Comrie¹⁵, who had been wounded in the Great War and who had then become an Isaac Newton student at Cambridge, where he obtained his doctorate for a thesis on the occultations of stars by planets. While still at Cambridge, Comrie became the Director of the Computing Section of the British Astronomical Association, which, incidentally, Downing had helped to found for amateur astronomers in 1890. Comrie produced the first edition of *The Handbook of the BAA* for the year 1922, and came to the USA to teach at Swarthmore College and Evanston. In 1925 he returned to England and joined the staff of the NAO; he soon became Deputy Superintendent.

Comrie then completely revolutionised the work of the Office^{16a}, by first introducing commercial calculating machines to replace the use of logarithms, and then by obtaining the use of punched-card equipment for evaluating the ephemeris of the Moon from E. W. Brown's new theory¹⁷. At the same time Comrie was redesigning the Almanac so that the edition for 1931, which was issued before Comrie became Superintendent in 1930, contained major changes in content and typography and a much greater amount of explanatory material.

Cowell never used a calculating machine, but he was able to carry out mentally accurate multiplications of 3-figure numbers faster than his assistants could check him using tables. On his 60th birthday he sat at his desk until 12 noon and then walked out without saying a word.

The period of transition 1930 to 1949

Cowell had tended to go back to the old system of paying staff on short-term contracts, but Comrie was anxious to build up the permanent staff of the Office and one of his first appointments was of Donald H. Sadler¹⁸, then a 22-year youth from Cambridge with one-year's postgraduate experience of numerical work.

At that time predictions of occultations of stars by the Moon were made by members of the BAA, and one of them, J. D. McNeile had

made a machine in wood that acted as an analogue computer. Comrie saw the value of this and arranged for the foreman of the workshop of the Royal Observatory, A. C. S. Westcott, to construct a similar machine in metal. He did the job in his own time for £100. The new occultation machine was used in the NAO for over thirty years.

Details of the machine and of the methods used for the calculations are given in a booklet on the prediction and reduction of occultations¹⁹. The preface acknowledges the kindness of Dr. James Robertson, the director of the (American) Nautical Almanac Office in communicating the method used in the selection of occulted stars.

Comrie was the first to propose the use of the standard equinox of 1950.0 for the computation of orbits and he designed the first edition of *Planetary Co-ordinates*, which was published in 1933 for the years 1800-1940. Details of methods of interpolation and other numerical processes were published in the booklet *Interpolation and allied tables*, which was printed from stereographic plates of the *Nautical Almanac* for 1937.

Comrie was probably most widely known as a maker of mathematical tables, which were renowned for their accuracy and typographical design. Unfortunately, he failed to make a clear separation between the official work of the NAO and the unofficial work for which he paid staff privately. As a consequence he was summarily dismissed in 1936 after the visit of an Admiralty team which inspected the work of the Office after a request from Comrie for more staff.

Comrie went on to set up the Scientific Computing Service^{16b}, but he died in 1950 before the era of electronic computers had begun. I regret that I did not meet Comrie, but several members of the NAO staff have written down their recollections of him.

Donald Sadler was made Superintendent, but, possibly because he was still very young, it was decided that he should report to the Astronomer Royal, then H. Spencer Jones (later Sir Harold), who finally produced convincing evidence that the errors in the predicted longitudes of the Moon and planets were due to irregularities in the rotation of the Earth. This had been suspected by Simon Newcomb and others, but there appears to have been a general reluctance to accept this hypothesis, possibly because it was not then possible to explain the mechanism satisfactorily.

Sadler carried through several projects started by Comrie, including the production of the first UK almanac for air navigation (for the

end of 1937), the publication in 1939 of the second volume of *Planetary Co-ordinates* (for 1940-1960) and the publication for 1941 onwards of the international almanac *Apparent Places of Fundamental Stars*, for which the calculations were made in several countries. The Office also published *Seven-figure trigonometrical tables for every second of time* in 1939 and *Five-figure tables of natural trigonometric functions* (for every 10 seconds of arc) in 1947.

Surprisingly, the exchange of astronomical calculations continued throughout the second World War, with neutral countries acting as intermediaries. Indeed, the NAO became an international centre for the prediction and reduction of lunar occultations in 1943, with H. W. P. Richards as the head of the section concerned.

The NAO was expanded during the war to produce, for example, 'Bomb Ballistic Tables' and to carry out computations for many other wartime projects. Eventually it became the operational centre for the Admiralty Computing Service^{20a}. After the war some of the additional ACS staff moved to the National Physical Laboratory to form the nucleus of its new Mathematics Division^{20b}.

During this period of intense activity, Sadler found the time and the energy to continue to act as the Secretary of the Royal Astronomical Society. He has given an account of this period in the chapter for the decade 1940-1950 in the history of the Society²¹.

After the war, in 1947, Sadler made the first of several visits to Washington, and it is clear that he established a very good working relationship with Gerald Clemence, who was then the Director of the NAO at USNO. These visits, and those of Clemence to England, were usually made in association with attendance at meetings of Working Party 52 of the Air Standardisation Coordinating Committee of the air forces of the USA and British Commonwealth. This visit proved to be the key that opened a long and successful period of cooperation between the two Offices. Most of the rest of my paper is dominated by this cooperation.

The period of unification, 1949-1969

After the move in 1949 of the NAO to Herstmonceux Castle in Sussex to join the recently renamed Royal Greenwich Observatory (RGO), Donald Sadler and Gerald Clemence carried through the unification of the almanacs of the UK and the USA. They had to persuade the navies and the air forces to change their practices in order to arrive

at a common content and format, and this was not easy.

The first almanac to be unified was the *Air Almanac*, for the year 1953. From then on, the UK and US editions had a common content, but were printed separately and had different methods of binding. The copy for the daily pages was produced in the USA, while that for the auxiliary and explanatory pages was produced in England; proof-reading was shared. Reproducible material was not only exchanged between the two Offices, but was made available very cheaply to other countries for use in their almanacs, either directly or after the language of the headings had been changed.

Sadler was largely responsible for the design of *The Star Almanac for Land Surveyors*, which was first issued for the year 1951 and which is still in use in nearly its original form almost 50 years later! He tried unsuccessfully to persuade Clemence to make this a joint publication.

I joined the NAO in 1951 and, like Sadler, I was then just 22, but I had not attended any astronomical courses at university — I had degrees in physics and mathematics, together with an interest in computing that I had gained while carrying out my PhD research on the daily variations of the Earth's magnetic field. My first jobs were given to me by Sadler so that I would learn about spherical and dynamical astronomy as well as about the computing techniques that were then in use in the Office. At that time, almost everyone had a manual Brunsviga calculating machine on their desks, there were a few electro-mechanical Marchant and Friden machines, two National accounting machines, one for decimal and one for sexagesimal arithmetic, and a set of Hollerith punched-card machines in a separate building.

The punched-card machines were on rental from the British Tabulating Machine Company (BTMC), which at that time had a marketing agreement with IBM and through which the Office acquired an IBM 602A calculating punch. This agreement was broken when IBM decided to compete with BTMC in the UK and the Office then had great difficulty in getting parts and support for the 602A, which was 'programmed' by wiring on a large plugboard, and in getting delivery of an IBM card-controlled typewriter.

One of my first jobs was to plan and oversee the calculation on the punched-card machines of daily values of the nutation in longitude and obliquity from new series that had been developed at USNO by Edgar Woolard. We used the method of 'cyclic packs' that had been developed by Comrie and the results were used in the computation

of the *Improved Lunar Ephemeris*, which was published as a Joint Supplement to *The American Ephemeris* and *The (British) Nautical Almanac* in 1954.

1954 was also the year in which Sadler and Miss Flora McBain, who had joined the Office in 1937, were married in secret; the wedding was attended by Sir Harold and Lady Spencer Jones and two former members of the Office. It may be noted that Sadler was a keen and proficient sportsman. The isolated position of Herstmonceux Castle resulted in the RGO having an active Social and Sports Club, in which members of the NAO played a prominent role in the early years.

Sir Harold Spencer Jones retired at the end of 1955 and Richard van de Riet Woolley, then the Director of the Mount Stromlo Observatory in Australia, was appointed as the 11th Astronomer Royal. His comment on landing — that space travel was ‘utter bilge’ — hit the headlines and delighted the cartoonists.

At about this time I was given the job of preparing a completely revised and expanded edition of the booklet *Interpolation and Allied Tables*. We started to do this in cooperation with staff of the Mathematics Division of the National Physical Laboratory, but we found that our target readers were different and so we went our separate ways. The NAO booklet was published in 1956, by which time I had started to prepare the companion booklet *Subtabulation*.

The first section of *Subtabulation* was intended for use with electronic computers, but the other two were primarily intended to provide a record of the methods that had previously been used in the Office. Sadler wrote the second section on the ‘end-figure method’, which used preprinted tables for manual calculations. He gave me the task of drafting the third section on the method of ‘bridging differences’, which was still being used on the National and Hollerith machines. A wide variety of formulae and precepts were available, but I could find no documentation on how they had been derived. I felt very pleased when I succeeded in developing a systematic way of producing such formulae.

I used to see the correspondence between Sadler and Clemence about the unification of the almanacs for marine navigation. My recollection is that it was Clemence who proposed using a layout with data for three days at each opening, but Sadler did much to fill in the detail of the layout that was eventually adopted. In this case, we produced the daily pages using an IBM card-controlled typewriter and

pre-printed ruled forms, which required the development of a special, but simple, technique to ensure that the columns of figures kept a constant distance from the rules.

The unified publication was called, simply, *The Nautical Almanac* and so for a long time there was much confusion with our main almanac, even after it had dropped the first half its name to become *The Astronomical Ephemeris*. The unification of the navigational almanacs was accompanied by a unification of the auxiliary navigation tables (mainly for RA/Dec to Alt/Az conversions), but here the UK was content to adopt the US publications with comparatively minor changes.

As early as 1952, Sadler had put forward a proposal for an *International Fundamental Astronomical Ephemeris* that would obviate the need for each major country to prepare and print high-precision ephemerides of the Sun, Moon and planets. This idea did not find general favour, although Germany gave up its *Berliner Jahrbuch* and took over from us the work of publishing *Apparent Places of Fundamental Stars*.

The concept of ephemeris time was introduced in 1952 and then during the 1950s the formal definition was changed twice from the original 'operational definition' initially favoured by Clemence to the formal definition that was eventually used. I attended some of the discussions about timescales when Clemence visited Herstmonceux; Professor Samuel Herrick participated in some of them as he spent a sabbatical year with us.

The introduction of ephemeris time demanded changes in the astronomical almanacs and so it provided an ideal opportunity to take unification one stage further. There was already a lot in common between the British and American astronomical almanacs, but there had to be a lot of give and take to get the final agreement on content and on the sharing of the work of computation and printing. In this case we produced the reproducible material for the first half, while that for the second half was produced in the USA. The change point was easily seen as different typographical founts were used in the two halves. There was also an agreement to disagree on spelling!

Unfortunately, Clemence could not get authority to change the title of the *American Ephemeris* to a common title as it would have required the approval of the US Congress. Our almanac was renamed the *Astronomical Ephemeris*. From 1960 onwards, the two almanacs were

identical in content, apart from the title page and other preliminaries, such as the list of the staff, but the colour of the UK edition was changed from blue to green.

Sadler and Clemence wished to strengthen the cooperation between the two offices by exchanging staff. As a consequence I spent a year in the U.S.A. after preparing the copy for *Subtabulation*. I worked at the U.S. Naval Observatory from February to September 1957 and then went to Yale University Observatory for a further five months. I gained experience in programming an IBM 650 electronic computer while trying to determine improved orbital elements for the satellites of Mars and I learnt about various aspects of celestial mechanics. More importantly, I developed a good working relationship with the staff of the NAO in the Naval Observatory. Further details of my experiences during this year are given in Annex 1 to this paper.

While I was in the USA, the (British) NAO moved into the new West Building on the hill to the south-west of the Castle. The staff immediately had the new and unexpected task of providing the first UK prediction service for artificial satellites, but I was disappointed to find on my return that Woolley would not support the work and that at the beginning of 1958 the task had been transferred to the Royal Aircraft Establishment at Farnborough (and later to the Radio and Space Research Station at Slough.)

Another disappointment was that the Admiralty had not approved our proposal that the NAO should have a English Electric DEUCE computer; instead it decided that we should have a BTMC (later ICT) 1201 computer. I realized that this would be technically inferior to the IBM 650, but I did not realize that I would have to write almost all of the basic software before we could use it for our work. My experience at USNO proved to be invaluable.

On my return I was given the task of editing the contributions from the two offices to the long-overdue *Explanatory Supplement to the Ephemeris*. One aim was to give a uniform typographical style throughout, but it was not possible to eliminate the differences in literary style nor in the approach to the methods of computation. Sadler and Woollard differed in both, and I sometimes had to insert extra material to give an alternative explanation or method. This is probably most noticeable in section 3 on systems of time measurement. The Supplement contains a brief account of the history of the Almanac and a list of the appendices and supplements to it.

The *Explanatory Supplement* was published only in the UK. Unfortunately, it turned out that Her Majesty's Stationery Office (HMSO) was unable to set up an effective sales system for it in the USA and so we had a lot of complaints about this aspect of the arrangements. Subsequently, we issued a series of *NAO Technical Notes* that gave information about various aspects of the work of the NAO; some of them were published later. A partial list of them is given in the 1992 edition of the *Explanatory Supplement*.

Sadler's flair for organisation had been recognised by the International Astronomical Union and he served as its General Secretary during the period 1958-1964. He did a lot of the work for this at the weekends — he would always go to his office after we had finished playing men's doubles tennis on Sunday mornings, usually with the Astronomer Royal, Woolley, and Albert E. Carter, who was the head of the machine section of the Office.

I suspect that Sadler's involvement with the IAU and other organisations was probably the reason why he did not learn to program, although I am sure that he would have made an excellent programmer. He probably delegated more responsibilities to me than he would otherwise have done.

My own involvement with the IAU began in 1963 when I was appointed secretary of the IAU Working Group on the System of Astronomical Constants. After this I had the task of writing a program to compute the fundamental lunar ephemeris, taking into account the new system of constants and the further corrections developed by W. J. Eckert, who had been Director of US NAO. I was able to start from a Fortran program that had been written by Neil Block at the Jet Propulsion Laboratory, but I had to develop the new program on an IBM 7090 in London as our own ICT 1201 was quite inadequate.

We were pressing for a better computer, but again I was thwarted as the Admiralty turned down our proposal for an IBM 360 system and insisted that we had an ICT (later ICL) 1909 system. This turned out to be much better than I had expected, but it did not allow us to exchange programs easily with USNO as I had hoped. We were, however, able to use it to compute the new lunar ephemeris. I also developed a system for automatic phototypesetting of tabular matter; this was used primarily for the *Astronomical Ephemeris* and the *Star Almanac*.

During the 1960s the cooperation between our two offices contin-

ued as various improvements were made to the publications. I believe that Sadler played a principal role in the design of the series of *Sight Reduction Tables for Marine Navigation*, which were published in 1971 onwards. His final task for the IAU was to organise the General Assembly in Brighton in 1970, and so at the beginning of that year I became Acting Superintendent until he formally retired in February of the next year.

The period of reduction, 1970-1989

During his period of office Woolley attempted to change the RGO from a public-service establishment to an astronomical research institute. Such changes became easier when the primary responsibility for the funding of the Observatory was transferred from the Ministry of Defence to the newly-formed Science Research Council in 1965.

The navigational work of the Office was supported by special funding from the Ministry of Defence. We could justify the occultation programme as a research activity, especially as it was extended to cover the occultations of radio and later X-ray sources. The discovery of the first quasar was an unexpected offshoot of the NAO's occultation programme. The NAO provided predictions for the occultations of radio sources, which were used to help to map their structures. Then Cyril Hazard observed one that behaved like a point source; W. Nicholson in the NAO was responsible for the reduction of the observed data to determine the coordinates of the source, and this led to the optical identification of 3C 273 as a quasar²².

The NAO did not have enough resources to carry out a major program of research or development in celestial mechanics — the US Navy was more sympathetic to this than the Ministry of Defence and, later, the SRC. Woolley, moreover, saw no value in the production of the *Astronomical Ephemeris* and in similar fundamental work. Consequently, early in 1970 I found myself faced with a decision by an SRC committee that we should cease to publish the AE. Fortunately, the committee was meeting at Herstmonceux and the chairman allowed me to speak to the committee. When I explained how our work was used by the international community and, in particular, how our material formed the first half of the *American Ephemeris*, the committee rescinded its earlier decision.

Sadler not only passed on to me the job of Superintendent of the NAO, but he nominated me for two IAU jobs, so that I became the

chairman of the IAU Working Group on Numerical Data and the IAU's representative on the Federation of Astronomical and Geophysical Services (FAGS). The former job also entailed me acting as the IAU representative on CODATA (the ICSU special committee for data for science and technology). I later became the secretary of FAGS. I found these activities extremely interesting, but they must have reduced the amount of effort that I put into the NAO work.

The international service for the prediction and reduction of occultations of stars by the Moon, which was led by Mrs Flora Sadler, was at this time primarily aimed at providing a uniform time-scale against which the variations in the rate of the rotation of the Earth could be determined. This aspect of the lunar occultation programme was, however, superseded by the availability of atomic time, but the expertise in the office was used by Leslie V. Morrison and his team to collect and re-reduce earlier observations, and so to improve considerably our knowledge of the variations in the 'length-of-day' since the 17th century. Later, Morrison also provided the technical back-up for Richard Stephenson's work on the use of the records of ancient eclipses for the same purpose²³.

The NAO also provided support for Gordon E. Taylor to allow him to follow up his personal interest in the occultations of stars by minor planets. Eventually this gave interesting results that could not then be obtained by other methods. We also like to believe that it was his prediction of the occultation of a star by Uranus as part of our regular programme that led to the discovery of the rings of Uranus.

As a further contribution to research, Dr. Andrew T. Sinclair, and, later, Dr. Donald B. Taylor, both of whom had been students of Dr. P. J. Message at the University of Liverpool, did, however, produce a series of papers on the motions of minor planets and satellites whilst also contributing to other aspects of the work of the office. (I knew Message well as he and I had had been at Yale at the same time.) Sinclair took over the work on the satellites of Mars that I had started at USNO in 1957 and he produced an improved set of orbital elements.

Sir Richard Woolley retired at the end of 1971 and was succeeded as Director, but not as Astronomer Royal, by Dr. E. Margaret Burbidge. She resigned after a short while and her place was taken in 1974 by Dr. Alan Hunter, who led the celebrations of the Tercentenary of the Royal Observatory in 1975²⁴. Under his leadership the various departments of the Observatory were grouped into Divisions and I was made Head

of the Almanacs and Time Division, so that I became responsible for administrative oversight of the Time Department, which was headed by Humphry M. Smith. Later, the Libraries and Archives Department was added to the Division.

At this time, the Computer (formerly Machine) Section of the NAO was made into a separate department within the A&T Division; Carter continued as its head. My increasing involvement in administrative and external activities meant that I stopped being an active user of the computer system and I was no longer able to keep up with the details of the technical developments in computing.

One of Woolley's criticisms of the *Astronomical Ephemeris* had been that it did not cater properly for the needs of astrophysical observers, and so I took the opportunity provided by the IAU General Assembly in Sydney in 1973 to try to find out what changes ought to be made. There was also a need to update the fundamental ephemerides to take into account the need for the use of timescales that were consistent with the theories of relativity.

We were also under renewed pressure to reduce the costs of producing and distributing the *Astronomical Ephemeris*. At that time we used to distribute about 100 copies of the *Advanced Proofs* of the AE several years in advance of final publication so that other countries could use our data in computations for their local almanacs. We also used to send copies in exchange for the publications of other observatories and institutes, but it was clear that in most cases these were not of equal value.

The eventual resolution of these matters required a lot of discussion between our two offices. During this period Dr. P. Kenneth Seidelmann succeeded Duncombe as Director of the US NAO and I am glad to say that the good relations were maintained. In our Office, Mrs Flora Sadler had retired in 1973 and Dr. Bernard D. Yallop had taken charge of the publications work of the NAO.

The most fundamental change was that the separate printing of the AE in the UK was stopped after the edition for 1980, although the UK continued to compute its share of the ephemerides and to provide reproducible material for the jointly-prepared almanac. I was very pleased when the Scientific Director of USNO, then Dr K. A. Strand, was persuaded to seek the approval of Congress for the change of name of the *American Ephemeris* to the *Astronomical Almanac*.

There were many changes in the arrangement of the material, and

variations in typeface occurred throughout the volume. The changes in the basis of the ephemerides took longer to implement and must have imposed a considerable extra load on the staff in USNO as we were unable to contribute our full share. The improved ephemerides were first included in the Almanac for 1984.

The advance distribution of advance proofs was stopped, but we expanded the contents of the next volume of *Planetary Co-ordinates* to include, for example, tabulations for the Moon. We first produced *Planetary and Lunar Coordinates* for 1980-1984 and the volume for 1984-2000 came later.

In the early 1970s the NAO had been party to a bid for a lunar laser ranging system to be built in the UK for deployment in South Africa, but that was not approved by the Research Council, possibly because we could not get appropriate support from any South African group. We did, however, get approval for Sinclair to spend a year in Australia to work on the LLR project at Orroral, near Canberra. This proved to be one of the keys to the later success of the satellite laser ranging (SLR) project, which replaced the photographic zenith telescope as the RGO's contribution to the determination of universal time and polar motion.

By this time the occultation program was obsolete and so several NAO staff moved to the Time Department to develop and operate the new satellite laser ranging system. Morrison was moved to the Astrometry Division and so he was not available to edit the new edition of the *Explanatory Supplement* as I had hoped. We did, however, contribute to the new edition which was edited by Seidelmann and published in the USA in 1992.

Between 1978 and 1988 I was heavily involved in the international MERIT project, which led to the setting up of the successful International Earth Rotation Service, and also in organising the activities of IAU Commission 5 (Documentation and Astronomical Data) of which I was President from 1985 to 1991. Consequently, more and more responsibility fell on Yallop. He took a greater interest in navigation than I had done and started the series of volumes of *Compact Data for Navigation and Astronomy* using the technique that we had introduced earlier for the daily ephemeris of the Moon in the *Astronomical Ephemeris*.

From Herstmonceux to Cambridge, 1989-1998

During the 1970s the RGO was subjected to a major review of its role, but it was eventually given responsibility for the management of the construction and operation of the Northern Hemisphere Observatory, as it was then called. The new observatory was established on the island of La Palma in the Canary Islands as part of an international observatory. The public service role of the RGO was also recognized, but as a third priority. The staffs of the NAO and of the Time Department were, however, cut after Professor Alec Boksenberg became Director in 1981 and several experienced members were encouraged to take 'voluntary premature retirement'.

Further reviews took place during the 1980s and it was eventually decided that the RGO should be moved to a new site at Cambridge, close to the Institute of Astronomy. I reached retiring age in 1989 before the move took place and I formally gave up my management responsibilities at the end of March. The Time Department was closed, although I was able to argue successfully that the SLR operations should continue at Herstmonceux.

Bernard Yallop was already responsible for the production of the almanacs and so naturally took over the formal title of Superintendent and the responsibility for obtaining the staff and funding for the operations at a time when the Research Council was reducing the role of the Observatory to that of supporting the UK telescope facilities on La Palma.

The staff of the NAO was reduced to 4 or 5 persons when the move to Cambridge took place in 1990, but it continued to fulfill its share of the cooperative work with USNO and to provide a public data service. Don Taylor also managed to find time to keep up some research in celestial mechanics.

I am not aware of the circumstances, but Yallop was given the task of meeting all the costs of the Office from the revenue from the sales of its publications and services. Prior to this the Ministry of Defence had paid the Research Council for the costs of the work done by the Office for the navigational publications, but had retained all the profits from the sales. Fortunately, in spite of the growing use of GPS, the sales of *The Nautical Almanac* were still high and the profits were sufficient to keep the Office alive.

Bernard Yallop reached retirement age in 1996 and Andrew Sinclair, who had worked in the NAO from 1968 to 1990, was given the

job of overseeing the work of the Office on a part-time basis, while continuing to be Head of the SLR Department of the RGO. He had an even rougher time as there was first of all a proposal to turn the RGO into a non-profit company and then the decision of the Particle Physics and Astronomy Research Council to close the RGO at the end of October 1998.

At one time it appeared that the NAO might be taken over by a major publisher, but eventually it was decided that the Office should go to the Rutherford Appleton Laboratory. Only three of the staff have moved; one of them, Catherine Y. Hohenkerk, gave an account of the post-1990 activities of the NAO in an article in the final issue of the RGO house magazine²⁵. It is ironic that another of them, Steve Bell, had recently written a guide to the total eclipse of the Sun in 1999 that is a bestseller²⁶. It is such a pity that the RGO is now itself in permanent eclipse, but we hope that the partial eclipse of the NAO will soon be over and that the UK will once again play a full and fitting role in the international services for astronomy and navigation.

Additional sources

Information about the origin and early development of the *Nautical Almanac* may be found in many books on the history of astronomy or navigation, but there are few accounts of the history of the Nautical Almanac Office apart from the paper that I prepared on the occasion of the tercentenary of the RGO²⁷. After his retirement, Sadler started to draft a general history of the Office, but he abandoned the project when he was unable to find any significant amount of original documents prior to 1930. (It appears that the archives were destroyed by Downing and Cowell prior to their retirements.)

Sadler went on to draft from memory *A personal history of H. M. Nautical Almanac Office 30 October 1930 - 18 February 1972*, but the manuscript was in an unchecked and unedited state when he died. After my retirement, I typed and edited the material and issued a small number of copies of a 'preliminary version' of the document in May 1993, in time for a reunion of NAO that was held at Greenwich. I was, however, unable to resolve some of the inconsistencies in the draft or to fill in some of the missing detail. Although this document makes fascinating reading for persons who have been connected with the Office, the general impression seemed to be that it would be not be suitable for general publication²⁸.

Since then I have continued to collect information about the history of the Office and have started to write up my recollections of my period of service from 1951-1989 as part of a more general account of the history of the RGO during the period that it was at Herstmonceux Castle from 1948 to 1990²⁹. I have also written articles about Downing, Cowell and Sadler for publication in the *New Dictionary of National Biography* that is being prepared by Oxford University Press. I understand that the earlier DNB articles on Young and Stratford have been revised and that new articles on Hind and Comrie have been written.

A chronological table of events relating to the *Nautical Almanac* and the NAO from 1767 onwards is given in Annex 2; it includes some items that have been omitted from the above account.

Finally, it seems to be appropriate to draw attention to a volume that is complementary to Dava Sobel's *Longitude*, namely that on Greenwich time by the late Derek Howse³⁰, since it includes much material that is relevant to the activities of the (British) Nautical Almanac Office.

Acknowledgements

I am indebted to the late Donald Sadler in many ways, but especially for choosing me to work in H. M. Nautical Almanac Office and then for giving me appropriate training and opportunities to participate in a wide variety of activities and to succeed him as Superintendent of the Nautical Almanac. In the particular context of this paper, I must acknowledge my possession of much material about the history of the NAO that he collected during his retirement²⁹. I have found much interest and enjoyment in reading his recollections and those of other members of the staff whom he encouraged to write to him about their experiences.

This is not the place to list all the those persons who have given me assistance in my searches for information about the NAO and its staff, but I would like to thank Adam Perkins, the RGO archivist, for his help during and between my visits to the Cambridge University Library, where there is a very large volume of material relating to the NAO from 1930 onwards.

Finally, I would like to express my thanks for the invitation to speak at the U. S. Naval Observatory Symposium to celebrate the 150th anniversary of the establishment of the U.S. Nautical Almanac Office.

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ANNEX 1

DUTY AT THE U.S. NAVAL OBSERVATORY IN 1957

George A. Wilkins

Donald Sadler, the Superintendent of H.M. Nautical Almanac Office in the Royal Greenwich Observatory, and Gerald Clemence, the Director of the Nautical Almanac Office in the U. S. Naval Observatory, had the idea of an exchange of staff to strengthen still further the cooperation between the two offices. At the end of 1956 I was told that, as the first step, I would spend about six months at the US Naval Observatory (USNO) and then a further six months at the Yale University Observatory, where I would have the opportunity to attend lectures on celestial mechanics.

The administrative arrangements for my visit were very unusual. While I was at USNO I became a temporary member of the staff and I was paid accordingly. I continued, however, to be on the staff of the RGO and I received my normal pay and a 'Foreign Service Allowance'. As a consequence I had to pass my USNO pay cheques to the British Embassy.

The anomaly in my position became very clear on the first day when I was sworn in by the Superintendent of the Observatory. It was agreed, however, that I could omit one sentence from the normal text.

At the time I was married and we had a son who was not quite two years old. Unfortunately, since my tour of duty was to be only one year and not the usual three years, the Admiralty were not prepared to pay the fares for my wife and child and my FSA was only that for a single man. Moreover, since my wife was not travelling officially, she could not have a diplomatic visa, and since she wished to come for a year, she could not have a visitor's visa. As a consequence, she had to obtain an immigrant's visa!

We crossed the Atlantic in S.S. Queen Elizabeth in February 1957, but owing to a dock strike in New York we landed in Halifax and then had a 40-hour journey by train to New York, where we stayed overnight before continuing to Washington.

After all this hassle we were delighted to stay in the Clemence's home in the grounds of the Observatory for about a week while we looked for a tolerable apartment that we could afford. Clemence also started to teach me to drive in his Volkswagen Beetle, but in order that I could get more practice I bought a second-hand car (a large

Plymouth saloon) which I then parked and drove on the Observatory roads until I was confident enough to take and pass the driving test. My wife and I were also helped by other members of the USNO staff, but especially by Dr. Raynor J. Duncombe and his wife Mrs Juliana S. Duncombe, with whom we developed a lasting friendship, and who soon became Uncle Ray and Auntie Julie to our son, Michael.

I had expected that I would share in the work of preparing material for the almanacs, but instead I was given the task of computing improved orbits for the satellites of Mars, which were discovered in 1877 by Asaph Hall at the U.S. Naval Observatory, then in Foggy Bottom. In particular, I was to try to obtain a more accurate value for the secular acceleration of the inner satellite Phobos, as a Russian astronomer, Shklovskii, had concluded¹ that the value obtained by Sharpless at USNO in 1945 implied that the satellite was hollow and therefore artificial!

This task would not only give me experience in solving a practical problem in dynamical astronomy, but it would also give me my first opportunity to write programs for an electronic computer — the Observatory was to take delivery of an IBM 650 computer shortly after my arrival in Washington. In fact, I started to test my programs on similar computers in the Pentagon and the Naval Research Laboratory.

While I was at USNO I was allocated a roll-top desk (previously used by H. R. Morgan) in the Library, and so I did not interact with the NAO staff as much as I had expected. I hope, however, that I made useful contributions to the development of useful communal software for the IBM 650 computer. In spite of my isolation, I did get to know quite a number of members of the staff of the Observatory, and over 50 of them signed the copy of *The American Ephemeris* that was presented to me when I left to go to New Haven, Connecticut, in September 1957.

While at the Observatory I was able to attend a weekend 'neighbours meeting' at the Yale University Observatory in New Haven, Connecticut, and meetings of the American Astronomical Society in Cambridge, Massachusetts, and in Champagne-Urbana, Illinois. In the autumn at Yale I attended lectures on, for example, lunar theory by Professor Dirk Brouwer and I continued my work on the satellites of Mars as I was able to use another IBM 650 there. Many years later I was pleased to find² that "At the time the Mariner 9 spacecraft went into orbit around Mars and began its observations of Phobos and

Deimos, Wilkins' theory provided the best predictions of the satellites' positions".

The Russians launched their Sputnik satellites in the autumn soon after we had moved to Connecticut, and the U.S. Army launched the first Explorer satellite while we were back in Washington in February 1958 for a 'neighbours meeting' at the Observatory. Duncombe was associated with the computation of the orbit of the satellite, and so Message and I were able to visit the computer center on Pennsylvania Avenue and see the large IBM 704 computer that was being used. We were also able to look around the adjacent exhibition about the Vanguard satellite project.

We returned home towards the end of the month; before doing so, I sold our Plymouth to Dr. J. Kovalevsky, from the Bureau des Longitudes, Paris, who had recently started a visit to the Yale University Observatory. I was later pleased to find that it gave him good service. Our transatlantic journey was again in S.S. Queen Elizabeth, on which we embarked in New York.

Unfortunately, no member of the USNO staff spent a similar period working in the NAO at Herstmonceux Castle. I am very grateful for the valuable experience that I gained at USNO and Yale, as well as for the friendships that I made at the time. These have been renewed subsequently by short visits and at meetings of the International Astronomical Union, where we have also established good relationships with the staff of the other organisations that contribute to the totality of international ephemerides.

Our son, Michael, returned, as a student, to the Naval Observatory in 1974 to work in the NAO for about seven months. He enjoyed the hospitality of Dr. & Mrs Duncombe and gained much benefit from the experience. Unfortunately, he died in 1977 in a mountaineering accident in the Swiss Alps shortly after graduating in mathematics from the University of Cambridge.

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2. The comment is by J. B. Pollack in *Planetary Satellites* (J. A. Burns, Ed., University of Arizona Press, 1977), p. 399.

ANNEX 2

CHRONOLOGY OF *THE NAUTICAL ALMANAC* AND OF
H.M. NAUTICAL ALMANAC OFFICE, 1767–1998

- 1767 First year of *The Nautical Almanac and Astronomical Ephemeris*, with tabulations of lunar distances, produced by Nevil Maskelyne, 5th Astronomer Royal.
- 1811 John Pond succeeded Maskelyne as Astronomer Royal.
- 1818 Thomas Young was appointed Superintendent of the Nautical Almanac; he was also the secretary of the Board of Longitude.
- 1829 Young died and Pond resumed responsibility for the *Nautical Almanac*.
- 1831 Lt. W. S. Stratford, then secretary of the Royal Astronomical Society, was appointed Superintendent of the Nautical Almanac.
- 1832 Stratford established the Nautical Almanac Office with permanent staff to replace the system of home-based computers and comparers.
- 1834 Major changes were introduced into the *Nautical Almanac* to make it more suitable for astronomical use.
- 1853 John R. Hind became Superintendent.
- 1891 A. M. W. Downing became Superintendent
- 1896 First year that Part 1 of the *Nautical Almanac* (containing data for navigational purposes) was published separately for the convenience of sailors.
- 1901 Ephemerides based on Simon Newcomb's tables and constants were introduced.
- 1904 The name of the Office was first given the prefix H.M. in the *Nautical Almanac* for 1907.
- 1910 P. H. Cowell became Superintendent
- 1911 Agreement was reached at a conference in Paris on the sharing of calculations between the principal ephemeris offices.
- 1914 First year of *The Nautical Almanac, Abridged for the Use of Seamen*.
- 1925 Leslie J. Comrie became Deputy Superintendent and introduced the use of calculating machines and also of commercial accounting and punched-card machines.
- 1930 Comrie became Superintendent and Donald H. Sadler joined the staff.

- 1931 Major changes and much explanatory matter were introduced into the *Nautical Almanac*.
- 1933 Publication of first volume of *Planetary Co-ordinates referred to the equinox of 1950.0*.
- 1936 Publication of *Interpolation and Allied Tables*, based mainly on extracts from the *Nautical Almanac* for 1937.
- 1936 Comrie was replaced by Sadler, who from 1937 reported to the Astronomer Royal, instead of directly to the Hydrographer of the Navy.
- 1937 First volume of *The Air Almanac* for Oct.-Dec..
- 1938 A booklet on *The prediction and reduction of occultations of stars by the Moon* was issued as a supplement to the *Nautical Almanac* for 1938.
- 1939 The Office was evacuated from Greenwich to Bath.
- 1940 The type for the *Nautical Almanac* was lost in a fire, started during an air-raid, at Hammond's printing works.
- 1941 First year of *Apparent Places of Fundamental Stars*, which was prepared by the Office for the International Astronomical Union.
- 1941 Start of publication of the series *Astronomical Navigation Tables*.
- 1943 The Office became an international centre for the prediction and reduction of occultations of stars by the Moon.
- 1943-1945 The Office acted as the operational centre for the Admiralty Computing Service.
- 1949 The Office moved from Bath to Herstmonceux Castle as part of the Royal Greenwich Observatory, and occupied temporary wartime 'huts'.
- 1951 First year of *The Star Almanac for Land Surveyors*.
- 1951 Installation of BTMC punched-card machines.
- 1952 The almanac for marine navigation was redesigned and re-named *The Abridged Nautical Almanac*.
- 1953 First year of the unified *Air Almanac* for use by the air forces of the Commonwealth and of the United States of America.
- 1953 Installation of an IBM card-controlled typewriter for the production of reproducible printer's copy.
- 1954 Publication of the *Improved Lunar Ephemeris* by the USGPO as a Joint Supplement to the British and American astronomical almanacs.

- 1954 Sadler and Miss Flora M. McBain, who had joined the Office in 1937, were married.
- 1956 Publication of a completely new edition of *Interpolation and Allied Tables*, which was reprinted many times.
- 1957 George A. Wilkins was seconded to work in the Nautical Almanac Office of the US Naval Observatory for 6 months and then to the Yale University Observatory for 6 months.
- 1957 The Office provided a satellite prediction service for the UK from October to December after moving into the new 'West Building'.
- 1958 First year of the unified *Nautical Almanac* for use by the Royal Navy and the United States Navy.
- 1958 Publication of the booklet *Subtabulation*.
- 1958-1964 Sadler was General Secretary of the International Astronomical Union.
- 1959 Last volume of *Apparent Places of Fundamental Stars* prepared by the Office; then by the Astronomisches Rechen-Institut, Heidelberg.
- 1959 Installation of an ICT 1201 electronic computer.
- 1960 First year of the unification of the British and American astronomical almanacs, but with separate titles as *The Astronomical Ephemeris* and *The American Ephemeris and Nautical Almanac*.
- 1961 Publication (by HMSO) of the jointly-prepared *Explanatory Supplement* to the unified astronomical almanacs.
- 1961 Publication of *Royal Observatory Annals* No. 1, "Nutation 1900-1959"; based on E. W. Woolard's series.
- 1965 Funding of the RGO (and NAO) was transferred from the Ministry of Defence to the newly formed Science Research Council.
- 1966 Installation of an ICT 1909 computer
- 1966 Walter A. Scott, Head of the Navigation Section, retired after more than 40 years service in the Office.
- 1968 A booklet *Man is not lost* was published to mark the bicentenary of the *Nautical Almanac*.
- 1968 First use of automatic composition for phototypesetting of the ephemerides in the first half of the *Astronomical Ephemeris* for 1972.
- 1970 Wilkins became Superintendent (but in an 'acting' capacity until Sadler formally retired from the post in 1971).
- 1971 Publication of the first volume *Sight reduction tables for marine navigation*, which was prepared jointly with US.
- 1972 Sadler retired after more than 41 years in the Office.

- 1974 Formation of Almanacs and Time Division of the RGO, with the separation of the Computer Department from the NAO.
- 1979 Publication of *Planetary and Lunar Coordinates* for 1980 onwards.
- 1980 Last year of the lunar occultation programme.
- 1980 Last year of the distribution of proof copies of Part 1 of the *Astronomical Ephemeris*.
- 1981 First year of *The Astronomical Almanac*, which was prepared and published jointly but printed in the USA.
- 1984 *The Astronomical Almanac 1984* contained a Supplement on "The introduction of the improved IAU system of astronomical constants, time scales and reference frame into the Astronomical Almanac". The planetary and lunar ephemerides were based on numerical integrations constructed at the Jet Propulsion Laboratory.
- 1985 Publication of the first volume of *Compact data for navigation*.
- 1989 Bernard D. Yallop became Superintendent.
- 1990 The Office moved with the RGO to Cambridge.
- 1991 The mode of funding of the Office was changed so that it became dependent on the revenue from the sales of its publications.
- 1992 The *Explanatory Supplement to the Astronomical Almanac*, edited by P. K. Seidelmann, was published in the USA by University Science Books, California.
- 1994 Responsibility for the funding of the RGO (and NAO) was transferred to the Particle Physics and Astronomy Research Council.
- 1996 Publication of *A guide to the 1999 total solar eclipse of the Sun*; later editions as *The RGO guide ...*
- 1996 Andrew T. Sinclair became Superintendent, while continuing to be Head of the Satellite Laser Ranging Department of the RGO.
- 1997 Last year of the British edition of the *Air Almanac*.
- 1998 The RGO at Cambridge was closed and the remaining three members of the staff of the Office (not including Sinclair) moved to the Rutherford Appleton Laboratory, near Abingdon in Oxfordshire.

NAVIGATION VS. ASTRONOMY:
DEFINING A ROLE FOR AN AMERICAN NAUTICAL ALMANAC,
1844-1849

Craig B. Waff
Encyclopedia Americana, Grolier Educational

Introduction

Some time after its initial publication in 1766 (for the year 1767), American ship navigators began using the annual editions of *The Nautical Almanac and Astronomical Ephemeris* issued by the British government to determine their longitude on the open sea. American use continued even after the nation's independence from Great Britain, and apparently was widespread enough eventually to justify American reprints of the publication. There is no known evidence that American navigators in the first half of the 19th century felt uncomfortable with this dependence on a foreign publication or that they clamored publicly for one prepared and published by their fellow citizens. Yet in 1849 the U.S. Congress passed legislation authorizing just such an independent American production of this type of publication. As will be shown in this paper, those who advocated an American almanac/ephemeris in the 1840s presented two different lines of justification, one which was most influential in persuading Congressmen to authorize its publication, and another which was uppermost in the minds of those who were given the initial responsibility for supervising the calculations upon which it would be based.

Maury's Advocacy for an American Nautical Almanac

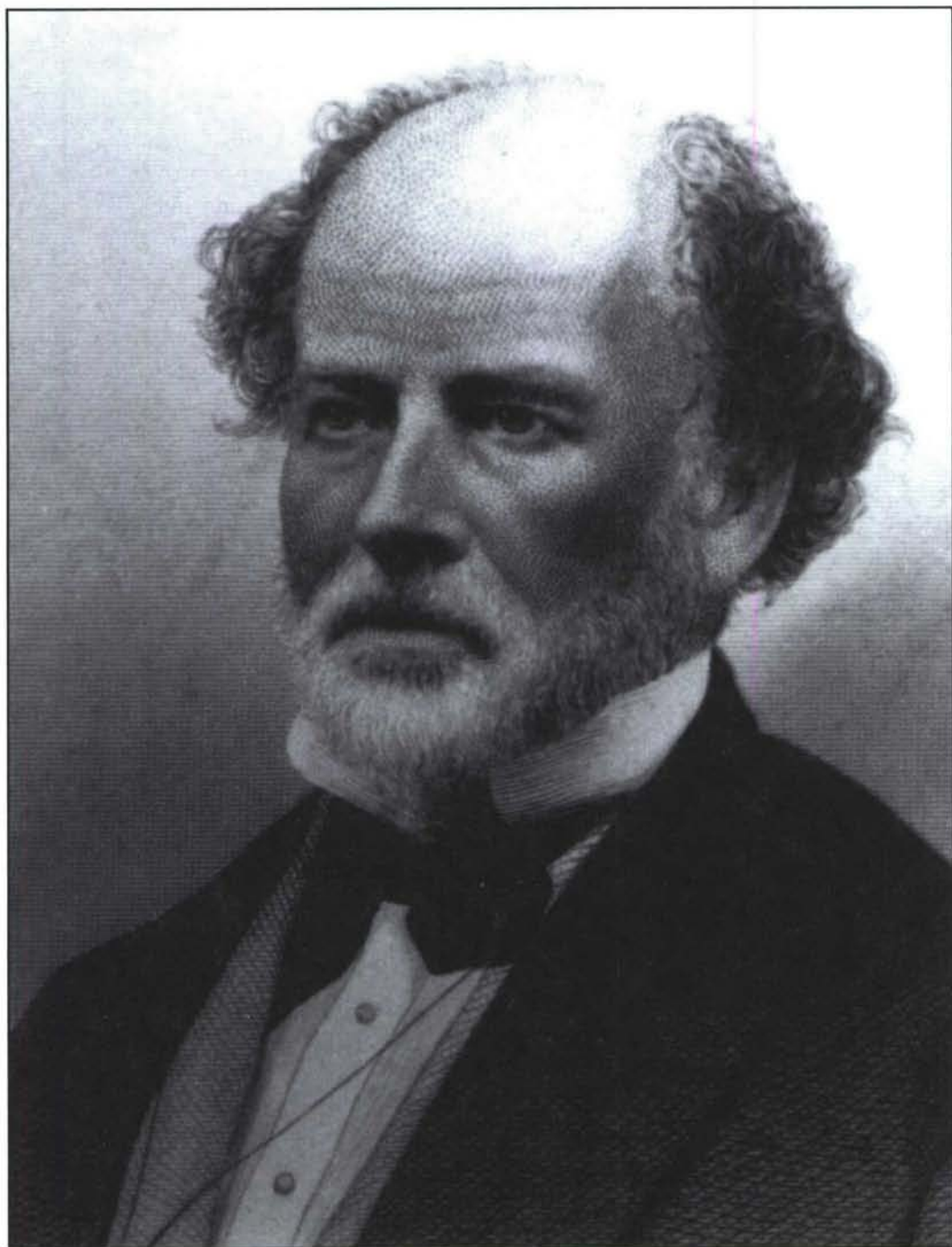
The Congressional authorization of an American nautical almanac in 1849 came about largely through the advocacy of Navy Lt. Matthew Fontaine Maury (1806-1873), who on 12 July 1842 was placed in charge of the navy's Depot of Charts and Instruments.¹ The depot had been established in 1830 on G Street in Washington, D.C., by Lt. Louis M. Goldsborough as a facility for rating seagoing chronometers. In 1833 the depot was placed in charge of Lt. Charles Wilkes, who moved it at his own expense to a site he owned 1,200 feet northwest of the Capitol. Lt.

James M. Gilliss (1811-1865) took over in 1838, when Wilkes left to command his Pacific exploring expedition. Upon Wilkes' return in 1842, he demanded the return of his property, and the depot was moved once again to temporary quarters on Pennsylvania Avenue, of which Maury was appointed to take charge five days after Gilliss tendered his resignation.

By this time, however, Gilliss had succeeded in getting Congress to appropriate \$25,000 for a new depot at a site west of the White House and close to the Potomac River. Following his resignation, he was ordered to supervise construction of the new facility and to acquire instruments for it. He accomplished the latter during a four-month trip to Europe (December 1842-March 1843), and by mid-1844 he had outfitted the new depot with the greatest collection of astronomical instruments--a 9.6-inch achromatic refractor, a 5.5-inch transit instrument, a 4-inch mural circle, a 5-inch transit in the prime vertical, and a 3.9-inch comet seeker--yet assembled in the United States.

Such an assemblage indicates that Gilliss, who from 1838 to 1842 had observed more than 10,000 transits of the moon, planets, and stars for the purpose of determining longitude differences between Washington and the points Wilkes visited during the latter's expedition, desired that the new facility be more than just "a mere Depot." In securing the appropriation for the new facility, he clearly stated to the House Naval Affairs Committee that "Astronomical, Magnetic, and Meteorological observations were to be a part of the duties required of the Officers attached to it: were, in fact, essential to the Navy."² And in an 1845 letter he stated that he had the "higher" aim "to place an institution under the management of naval officers, where, in the practical pursuit of the highest known branch of science [astronomy], they would compel an acknowledgment of abilities hitherto withheld from the service."

Gilliss had hoped to be named superintendent of the new depot, but Secretary of the Navy John Y. Mason instead appointed Maury on 1 October 1844. Gilliss was clearly disappointed and soon after privately expressed his concern that Maury had entirely different plans for the depot: "If it is to be an observatory, Maury is not the man to be at its head, unless he has an entirely different taste from that induced by his previous life and labours."³ Gilliss's negative assessment of Maury was undoubtedly influenced by the fact that the latter had little formal training in astronomy and was best known as an advocate for naval reform and for the improvement of hydrography, not astronomy.⁴ Gilliss may



Matthew Fontaine Maury

also have suspected that Maury been placed in charge of the temporary depot, as well as the new facility, primarily because of his reputation as a naval reformer and because of political connections.⁵

Perhaps anticipating that some individuals, particularly in the fledgling American scientific community, might express disapproval of Mason's appointment of him rather than the popular Gilliss and question his competence to direct the new facility, Maury quickly recognized the necessity of justifying the program of work he envisioned for the new depot. Thus on 7 November 1844, just over a month after his appointment, he addressed a letter to his direct supervisor, Commodore William Montgomery Crane, the chief of the navy's Bureau of Ordnance and Hydrography, in which he declared that with the newly acquired instruments and a small increase in staff "much may be done that would prove in itself not only useful & important to the Navy, but would tend in no small degree to wipe away the reproach which has been so often cast upon the country on account of the meagerness of its contributions to the general fund of Nautical science."⁶ The need to advance nautical science in general, rather than the more narrow program of purely astronomical science seemingly advocated by Gilliss, was, in Maury's view, the primary mission of the depot, and he left little doubt that the work assignments that he assigned the depot's staff would be selected with that mission in mind.

Maury's proposed work program was primarily shaped by his concern over how dependent American ships were on foreign, rather than American, labors for navigating both near and far away from home. He pointed out to Crane two particular examples of this dependence. One concerned the accurate knowledge of the location of shallow waters that navigators on ships traveling along the coast and entering and leaving the harbors of ports needed to have to keep their vessels from running aground. But, Maury observed,

Up to this time our public Ships not only depend upon other nations for their Charts of distant seas, but also of our own waters. ... The Charts used by an American Man of War when she enters the Chesapeake bay on her way to this city are English & we are dependent upon the English Admiralty for them. The only charts we have of our own Lakes & inland waters are procured by this office from that board.

Maury did not seek to secure work for the depot to lessen this particular dependence, for he was certainly aware that the U.S. Coast Survey, an agency within the Department of the Treasury, had been given the assignment of charting the coastlines and port harbors.

While in charge of the temporary depot, however, he had already begun a different kind of charting project--not of coastlines and harbors, but rather of the oceans and other open seas. Upon arriving at the depot he had discovered in storage a mass of dusty old logbooks that contained the daily record of nearly every voyage made by U.S. Navy ships since the service's founding. Upon studying and analyzing the most detailed of the logbooks, Maury became convinced that by extracting from them information regarding the force of winds and the direction and speed of ocean currents encountered, he could determine the average wind and current conditions that a ship might encounter during an oceanic voyage at a given time of year and identify natural paths or sea lanes that, if followed, would reduce the duration of a voyage between two ports and unnecessary loss of life at sea. He soon directed his staff to begin tediously collating such information from the logbooks, and he also began advocating to his superiors the need for systematic collection of wind and current information from all navy ships.⁷

Maury's awareness of a second type of American dependence on foreign labor for navigational aid undoubtedly stemmed from his own seaduty experience. During three extended tours aboard Navy ships that had permitted him equivalently to circumnavigate the globe, he had taught himself basic astronomy and navigation.⁸ Seeing a need to instruct midshipmen on the mathematical principles that formed the basis for finding longitude at sea by lunar observations, Maury in 1836 had written *A New Theoretical and Practical Treatise on Navigation*. It was a highly successful book that was republished in 1843 and that, on 4 September 1844, only a month before his appointment as superintendent of the new depot, was made, by a General Order signed by Mason, the chief textbook on navigation for midshipmen.⁹

But Maury was well aware, as he pointed out to Crane, that American navigators, for the calculation of longitude by astronomical means, were still dependent upon foreigners for one crucial element:

We cannot shape a true Course, nor steer from one port to another without realizing our entire dependence upon other nations

for all the elements of calculation by which it is done. ... [B]ut for the Nautical Almanac of England or some other nation, our absent ships could not find their way home nor those in our ports lift their anchors & grope to sea with any certainty of finding their way back again.¹⁰

Since at least 1820, the Navy had ordered, for its ships about to depart for sea, abridgments of the British *Nautical Almanac* that the New York-based nautical publishing firm E. & G. W. Blunt had issued (beginning in 1811) under license from the British Admiralty.¹¹ The responsibility for such purchases was at some point assigned to the depot, and Maury himself in the fall of 1843 had ordered 75 copies of the 1846 almanac, 25 copies of the 1847 almanac, and 10 copies of the 1848 almanac. And just prior to his letter to Crane, he had placed an order for an additional 50 copies of the almanac for 1848.¹² (Given the multiyear duration of some Navy ship voyages, almanacs were generally published and purchased several years in advance of the year in which they would be used.)

The construction and outfitting of the new depot, in Maury's view, gave the Navy the means to eliminate the country's dependence on foreign almanacs. With the depot's newly acquired astronomical instruments and "the addition of a comparatively small force," Maury informed Crane, "all the observations & calculations for the American Nautical Almanac can be made here, and that too for a sum of money but little, if any, greater than that which we now annually pay to the English Gov^t, for having the calculations made for us."

Perhaps at the instigation of Crane, Maury on 18 November 1844 addressed an almost identical letter¹³ to Mason, who in his report to Congress issued one week later, noted that the instruments purchased for the observatory had recently been installed, and added that they might

be advantageously employed in the necessary observations, with a view to calculate nautical almanacs. For these we are now indebted to foreign nations. This work may be done by our own naval officers, without injury to the service, and at a very small expense.¹⁴

No action was taken by Congress on the almanac proposal during the second session (2 December 1844 to 3 March 1845) of the 28th Congress,

but in September 1845 one Congressman, Joseph R. Ingersoll (Whig-Pa.), having either read Mason's report or been directly lobbied by Maury, predicted that "astronomical ephemerides will be here annually produced which will enable the navigators of our own military and mercantile marine to keep their path securely upon the ocean in patriotic reliance upon the calculations of their countryman."¹⁵

The next annual report of the Secretary of the Navy (who was George Bancroft from March 1845 to September 1846, when Mason returned to the post after serving as Attorney General during the first year and a half of the Polk Administration) to Congress did not include a specific request for an American nautical almanac, but attached to it was another letter from Maury to Crane, in which the depot superintendent noted how remarkable it was that a nation that was now second in the world in maritime importance had contributed so little "to the general stock of nautical information without which our vessels could not cross the seas--without which our commerce could not exist." Bemoaning that fact that we were "always borrowing heretofore," Maury proclaimed that "it is time that we should become lenders at least of a proportionate part of this information." He noted that his office now had the means except one to alleviate this situation by obtaining the data necessary for "a nautical ephemeris of our own," rather than continuing to depend on the British or other foreign nautical almanacs. The exception was a 48-inch meridian circle for determining accurate atmospheric refraction corrections.

Apparently not waiting for Congress to act on his proposal, Maury reported that his staff had already begun a series of observations for "the preliminary determinations." Maury insisted the data to be used in the proposed almanac should be *wholly* American, or else an American almanac should not be computed at all:

If we borrow one element of the work from foreign observatories, it would be more creditable to borrow the whole. If we use the declinations as established at Greenwich [the site of Great Britain's Royal Observatory], let us use their right ascensions also. The same data will necessarily give the same results, and if we suffer other people to procure these for us, or a part of them, let us not attempt anything ourselves, but continue to allow them to make the calculations also.¹⁶

Maury's linkage of an American almanac with American-only observations may have been partly due to some excessive patriotic feeling. Only a month and a half earlier, he had told Benjamin Peirce, America's leading mathematician, that "Bessel's and other tables [of refraction] are good enough, very good they are, - But they are not of Yankee manufacture."¹⁷ But more importantly, the linkage, in Maury's view, was essential for the continuing operation of the depot's recently acquired astronomical instruments, or what he now began calling the "Observatory." As he would explain to Peirce in late December, "So far I have felt it to be my duty to lay ourselves out upon the Sun, moon, planets and principle [*sic*] fixed stars with the view of data of our own for a Nautical Almanac: for without the visible and tangible fruit of a Nautical Almanac the Observatory will not be supported."¹⁸

Congressional Consideration and Approval

Maury did in fact actively lobby for an ephemeris, for in mid-January 1846 he reported to Peirce that his "friends" on the House Committee on Naval Affairs had promised to insert in the Navy appropriations bill an amendment providing \$5,000 for computing and publishing a nautical almanac.¹⁹ One of those friends may have been Isaac Edward Holmes (Dem-S.C.), the chairman of the committee from 1846 to 1847, to whom Maury addressed a letter in early February in response to a request to "give you my views ... as to the manner in which the usefulness of this office may be greatly & advantageously increased." Once again requesting the authority to compute and publish a nautical almanac "under the direction of this office," Maury made an economic argument that would have appealed to a legislator of any era:

If the question be reduced to an affair of dollars & cents, the account would balance in our favor; for if we take into account, as we should, the amount which we now annually pay England for making the calculation for us, & add it to the amount which could be realized from the sale of the work to American merchantmen & others, we should have a sum that would more than pay our own Computers.²⁰

As he had with Peirce, Maury suggested that \$5,000 or \$6,000 would be sufficient to defray the initial expense of computation and publication.

Maury's Congressional friends carried out their promise on 11 June 1846, when the Naval Appropriations Bill for the coming fiscal year (1 July 1846-30 June 1847) finally came up for a floor debate late in the first session (1 December 1845-10 August 1846) of the 29th Congress. One of the friends was Frederick Perry Stanton (1814-1894), a 31-year-old Democrat from Tennessee (the state where Maury had spent most of his childhood), who used the occasion to propose an amendment that would set aside \$5,000 for "computing and publishing, under the direction of the Superintendent of the Observatory, the American Nautical Almanac, to be calculated for the meridian of Washington city."

Stanton, a first-term representative who upon entering Congress the previous year had been assigned to the Naval Affairs Committee (which had "directed" him to propose the amendment), was soon giving speeches that were filled with a wealth of scientific nautical information. He was also quickly impressing influential colleagues. In 1849 the future U.S. president James Buchanan (who would appoint him secretary of the Kansas territory in 1857) recommended him as a second in command on the Ways and Means Committee, telling a colleague that he considered him "the most promising" among the younger members of the last Congress. He described Stanton as "able, faithful, industrious, and persevering" and having few superiors for "practical sense and sound judgment."²¹

Stanton and Holmes, who immediately followed him in the floor debate, were members of the Democratic Party, which had an almost 2-1 majority over the opposition Whigs during the 29th Congress (1845-1847), but both apparently anticipated resistance to the proposed additional appropriation from their fellow party members. The construction of the Observatory and the purchase of its instruments had been funded during a period when the opposition Whigs were in the majority, and the two Democrats may have suspected that many of their fellow party members might not be too keen to support a further appropriation for what may have been perceived as a particularly Whig project.²² The Democrats had of course for many years vigorously opposed the proposals for a national observatory made by John Quincy Adams, a former president of the United States (1825-1829) and since 1830 a Whig representative from Massachusetts.

The initial tactic of Stanton and Holmes was to minimize the expense involved. Stanton, apparently having read Maury's letter to

Holmes, began his defense of the amendment by pointing out that the sale of the almanac "would reimburse the Government for every dollar here proposed to be spent." And Holmes, comparing the almanac appropriation with the "vast expense" of \$15,000 to \$20,000 per year that already been spent employing men at the Observatory to make the required observations, which he (as well as Stanton) claimed were now "all in our possession," rhetorically asked "were we going to refuse the small sum necessary to turn them to account, and practically put them in the possession of the country? After the observations had been made, corrected, and digested, for a work of this high scientific character, were they all to be lost because Congress would not publish them?"

The initial attack, however, focused not on the expense of producing an American almanac, but on whether an American-produced almanac would be safe for American navigators to use. Maury in his letters had said nothing about how the proposed almanac would actually be produced, but William H. Brockenbrough, an apparently well informed Democrat, who had entered Congress only five months earlier representing the just-admitted state of Florida, attempted such an explanation for his colleagues and pointed out the absolute necessity of the highest accuracy possible:

The astronomical observations on which it [the British Nautical Almanac] was founded were made by different individuals, as were the tables constructed upon them: these were then brought together, collated, and corrected; and still, after all the pains and solicitude to attain entire accuracy, some mistakes still occurred; and a vessel relying on any of these erroneous figures, and directing her course on conclusions founded on such a basis, might be led into circumstances of great danger.

Brockenbrough argued that the British Nautical Almanac had been made highly accurate at a vast cost to the British government--an expense that the United States government would be unable to match. He also pointed out that it was the production of the most learned and scientific men in Europe and that it "was not a thing to be done in a day," possibly trying to leave the impression that Maury's observatory had not been in existence long enough to make the necessary number of observations and that his staff, while highly esteemed, were in quality no way comparable to their European counterparts.

Adams was quick to recall that "the learned man and astute observer" Nathaniel Bowditch had for many years detected errors in the British Nautical Almanac, and he expressed hope that an appropriation for a American Nautical Almanac would be a continuing one, in order that "through the skills and exertions" of the Observatory astronomers the latter would eventually "become the most correct publication any where in existence." But most of the vocal supporters of the amendment seemed content to portray the proposed publication of an American nautical almanac as an important symbol of national pride. Stanton felt "there ought to exist some just pride, some American feeling in this matter." Basing the computation of the almanac upon the Washington meridian would, in his view, "mark it as an American work, and as such, commend it to the affections of every American sailor." Ingersoll, stating that the Observatory astronomers were looking forward to rendering their country free from all dependence on foreign scientific labors, considered such an accomplishment as giving him "a source of unfeigned congratulation ... that we were able to take our place among the other nations of the world in the production of a work of this high scientific character." And Thomas Butler King (Whig-Ga.), who exclaimed that he contemplated the prospect of an American almanac work with "feelings of exultation," insisted that its publication "could not but be gratifying to every one who was alive to the feeling of national pride."

Brockenbrough, still not convinced that the proposed American almanac could be as accurate as the existing British one, replied that such a justification was inappropriate and that he "should be very sorry to see the use of [the latter] discontinued and the safety of our Navy jeopard[iz]ed for the sake of indulging an American feeling, however just and laudable." He portrayed the potential adoption of the amendment as enabling the Observatory to "making an experiment" in the production of an almanac similar to the British one. He foresaw it leading either to a reprint of the British almanac, in which case the appropriation was unnecessary, or an entirely original work of uncertain accuracy, which he would oppose as unsafe.²³

The amendment came up for a vote four days later and was defeated by a vote of 102 to 86, with 37 congressmen not voting.²⁴ One might attribute the amendment's defeat at least partly due to Brockenbrough's criticism, but an examination of party affiliations indicates that voting was primarily along party lines. The Whigs voted

59-5 in favor of the amendment, while the Democrats voted 96-20 against it. (Yea votes were also cast by all three congressmen identified as American party members and by two congressmen erroneously identified as entering as members of the Republican Party, which did come into being until 1856. Three congressmen whose affiliations are not given split 2-1 in favor of the amendment. Of the 37 congressmen who did not vote, 30 were Democrats, and 7 were Whigs.)²⁵

In his annual report issued in December 1846, Secretary of the Navy Mason once again requested an appropriation for a nautical ephemeris.²⁶ Stanton and other supporters of the Almanac proposal did not attempt to introduce a similar amendment to the naval appropriations bill in 1847, however, undoubtedly reasoning that its chance of passage was slim with the Democrats obviously still in the majority during the second session of the 29th Congress (which met from 7 December 1846 to 3 March 1847) and with the Mexican War, begun the previous year, still being fought and commanding great expense.

The 1846 elections, however, restored the Whigs to power in the House, and the war was winding down as the 30th Congress met for its first session (6 December 1847-14 August 1848).²⁷ Likely aware of this change in political direction, Maury, only three weeks before the session started, addressed a requested letter to Adams (subsequently published in *The Southern Literary Messenger*) that provided a lengthy description of the Observatory, and he used the occasion to argue that "The reasons and considerations which call for the establishment of national standards of weights and measures, call with like force, propriety and urgency for a national standard of Astronomical results," that is, a nautical almanac.

Apparently having become enlightened regarding how much work would actually be involved in computing such a work, Maury conceded that he himself could not superintend such a publication in detail without neglecting his other duties. He envisioned his responsibility as having "the general direction of it, so far as to say what it should contain, from what sources the materials to be embodied in it should be obtained, and what tests, examinations and proofs it should undergo in the preparation, etc." He advocated "a special and subordinate Superintendent, whose duties should be confined to the details of the work and nothing else," and who would have the assistance of a small corps of computers. Maury pointed out to Adams that each calculation needed to be performed twice,

and by at least two computers working independently, in order to assure the highest accuracy.²⁸

Undoubtedly at the prompting of Maury, Secretary Mason, in his annual report issued on the first day of the new congressional session, once again requested authority for a nautical almanac, this time specifically asking for an appropriation of \$6,000.²⁹ Soon afterward, in line with the organizational scheme that he had outlined to Adams, Maury drafted a specific amendment to be inserted in the naval appropriations bill:

And be it further enacted, That, for preparing for publication, from the observations made at the National Observatory, the American Nautical Almanac, to be calculated for the meridian of Washington, six thousand dollars, including fifteen hundred dollars for the pay of the superintendent of the same, in addition to the pay of a lieutenant in the navy, be, and the same is hereby appropriated, out of any money in the treasury not otherwise appropriated: *Provided*, Said superintendent shall be either a captain, commander, or lieutenant in the navy of the United States: *And provided further*, That the Secretary of the Navy shall cause copies of this work to be sold at the cost of publication, with the addition of ten percent.

Maury gave the draft amendment to King, the chairman of the naval affairs committee during the 30th Congress, who in turn passed it on to Adams. The plan may have been to allow Adams, who had endured derision for many years for advocating a national observatory, the honor of proposing the funding, sure to be passed by the Whig-dominated 30th Congress, of an almanac that would be produced at what had in fact become such a facility. Adams passed away on 23 February 1848, however, with the whereabouts of the draft uncertain but likely still in Adams' desk in the House chamber.

Maury was undoubtedly relieved to hear from a fellow naval officer, Lt. Charles Henry Davis (1807-1877), that King promised to ask for the draft amendment and present it on the House floor "with the authority of the deceased patriot." Davis expressed hope that the paper, which he considered would "have a national value coming from Mr Adams desk," was not lost.³⁰ The draft amendment was indeed recovered,

and King offered it on the House floor on 15 June, when the naval appropriations bill for the coming fiscal year came up for consideration. The expectation that it would be easily passed was quickly dashed, however, when Georgia representative Howell Cobb, the parliamentary leader of the Democrats, questioned "whether there was any existing law to authorize this expenditure?," to which King had to answer no. Cobb (who would become speaker of the House during the 31st Congress and Secretary of the Treasury in the Buchanan Administration) knew there was a House rule forbidding the insertion in appropriation bills of anything not authorized by previous law and requested that Richard W. Thompson of Indiana, presiding over the House floor this day, rule King's insertion out of order. Thompson proclaimed that "his personal opinion coincided perfectly" with Cobb regarding the rule, but noted that such insertions had so often been admitted and inserted by House votes, that he had "felt constrained to bow to the decisions of the House rather than follow his own judgment," and he thus ruled the amendment to be in order. After Robert McClelland (Democrat-Mich.) pointed out that such precedents had been admitted only when no objection had been made, the House voted to reverse Thompson's decision and rule King's insertion out of order.³¹ (Neither Cobb nor any other Democrat had felt it necessary to object in 1846 to Stanton's similar insertion, because obviously they knew their party had enough votes to defeat it.)

To avoid such a parliamentary defeat in the second session of the 30th Congress (4 December 1848-3 March 1849), Maury for the first time included a specific sum of \$6,000 for "calculating, printing, and publishing the Nautical Almanac" in the estimate that he submitted in late October to Commodore Lewis Warrington, who had succeeded Crane as chief of the navy's Bureau of Ordnance and Hydrography in 1846. Warrington and Secretary Mason did likewise, and thus a provision for a nautical almanac was in the naval bill submitted to the House.³²

Because Maury apparently forgot to inform his Congressional friends about this strategy, Stanton on 1 February 1849 proposed an amendment requesting \$5,000 (the sum asked for in the amendment he had offered in 1846) "for preparation and publication of the American Nautical Almanac." As he and other supporters of the Almanac had done in 1846, Stanton argued that publication of an almanac was essential for national pride:

It was important to the character of the Government that our national vessels should be guided by such a work, published in our own country. There was no question that the work at our observatory was done as well as the work at any Observatory in the world. There was no question that our Government could put forth a more complete and accurate work of this description than any other country in the world. It was important to the character of the country, it was important to our national pride, it was important to the national honor and independence, that this work which had been so often recommended by the Secretary of the Navy, and which now recommended itself to the favorable consideration of every liberal mind, should be adopted.

Stanton quickly withdrew the amendment, however, upon learning that funding for an almanac was already included in the Secretary of Navy's estimate for naval expenditures.³³ Apparently realizing that they had been outmaneuvered, Democratic opponents of the Almanac made no attempt to delete the almanac provision from the naval bill, and thus Stanton was able to assure Maury three days later that the appropriation for the almanac "will certainly be made."³⁴ With the passing of the Naval Appropriations bill by both houses on 3 March, the provision for preparing and publishing an American-made nautical almanac, for which Maury had relentlessly advocated and lobbied for more than four years, became effective for the fiscal year beginning 1 July 1849.

From the 1846 House floor debate and Stanton's speech in 1849, it seems clear that most Congressional supporters of an American-made nautical almanac felt (as did Maury, upon whom they depended for technical information) that it would find its only use at sea. While some expressed hope that an American almanac could be made more accurate than the existing European ones, neither they nor Maury offered any specific explanation as to how this was to be accomplished, or provide any evidence that the existing almanacs were not already sufficiently accurate for the practical needs of navigators. Rather, the main justification that they and Maury offered for authorizing an American-made almanac was to enable American navigators to remove themselves from dependence upon foreign labor. By doing so, they argued, the federal government would be taking a major step that would demonstrate, symbolically at least, that the United States was becoming a major power in the world.

The Advocacy for a More Accurate Astronomical Ephemeris

On the eve of the passage of the bill authorizing the Almanac that Maury had long advocated, however, there appeared, in the January 1849 issue of *The American Journal of Science and Arts*, an anonymously written two-page note that endorsed government sponsorship of an ephemeris that would be constructed for purposes quite different from those advocated by Maury and his Congressional friends.³⁵

The author reported that American astronomers had become so much encouraged by "the recent rapid progress of their science in this country"--possibly an allusion to the building of numerous astronomical observatories in the United States in the 1830's and 1840s³⁶ and the role that Sears Walker and Benjamin Peirce had played in determining the actual orbit of the newly discovered planet Neptune³⁷--that they had begun clamoring for "an ephemeris of their own." Apparently well acquainted with how Maury's proposed nautical almanac had been justified by his "friends" in Congress, the author insisted that the ephemeris desired by astronomers should not be undertaken "merely as an object of national pride, nor for the sake of being independent of the labors of other countries"; the country's "title to distinction" in science, he argued, "will be judged by the intrinsic value and importance of her contributions to science itself." The question that should be asked, in his view, was not simply "shall the United States have an astronomical ephemeris of their own?," but rather "does *astronomy* need a new one and a better one than it already possesses?"

A new, improved ephemeris was indeed needed, according to the author, because the ephemerides of the sun, the moon, and the planets given in the British, German, and French almanacs were derived from tables of their motions that were anywhere from 15 to nearly 40 years old.³⁸ The ephemeris of the sun was prepared from Francesco Carlini's 1833 tables³⁹; that of the moon was derived from Johann Karl Burckhardt's 1834 tables⁴⁰; that of Venus, Mars, and Mercury were generated from Bernhard August von Lindenau's 1810, 1811, and 1813 tables⁴¹; and that of Jupiter, Saturn, and Uranus were produced from Alexis Bouvard's 1821 tables.⁴² From the numerous observations of the sun, the moon, and the planets that had been made since, the author was confident, important corrections could be deduced for every element involved in the construction of the tables. Such a situation, he argued,

presented American astronomers with a extraordinary opportunity to make an important contribution to the advancement of their science:

The great work, therefore, which invites the labors of American astronomers is a full revision of these tables, or rather of the theories of the sun, moon and planets, indeed of the whole solar and stellar systems, and the construction thereon of *new* tables which shall bring in all modern observations at Greenwich, Cambridge, Oxford, Edinburgh, etc., in Great Britain; at Paris, Berlin, Pulkova, Königsberg, Munich, Vienna, and many other places on the continent; at Washington and other places in our own country. This would be a work worthy of the nation, and might engage our ablest astronomers and computers.

Although he did not call attention to it, the author may well have been trying to contrast the scope of this proposed project with Maury's plans, as outlined to Crane in 1845, for using only American observations.

The author of the *Journal* article made it clear that the increased accuracy of the work that he was advocating was for the benefit of astronomers, not navigators. The "astronomer engaged in improving the science itself" requires the extreme of accuracy, he observed, while the navigator needed "only such a degree of precision as will enable him to determine his position within certain practical limits." An American almanac made "by interpolating the European books to the meridian of Washington" or "by making separate computations from the same tables" might be sufficient for the navigator, but it "would add nothing to the stock of astronomical knowledge and little or nothing to the scientific reputation of the country." The author here appears to have had in mind not the casual observer of celestial phenomena or the college professor teaching the basic principles of astronomy, but rather the practical astronomer, that is, the astronomer endeavoring to ascertain the position of his observatory relative to some other point (such as the National Observatory) or the surveyor/topographical engineer out in the field similarly determining as accurately as possible the relative position of some specific point of land.

Obtaining the desired accuracy for the work that he was advocating would require the cooperation of the country's ablest astronomers, the author insisted (here apparently referring to the mathematicians and astronomers well versed in celestial mechanics), and that in turn would

require having a superintendent "whose scientific character shall command the confidence of mathematicians." The author was disturbed that the amendment proposed in the last session of Congress for an "American Nautical Almanac" would have required that the work be superintended by a Navy captain, commander, or lieutenant. He acknowledged that a suitable officer might be found--"indeed, we hail with delight every thing that tends to promote or encourage scientific attainments among them"--but such a restriction, he argued, "would pronounce our professed astronomers, who devote their lives to the science, to be less competent to take charge of important astronomical works than those who by profession are devoted chiefly to other pursuits." Surely this could not have been the intention of the "originator" of the amendment, the author insisted; rather,

It was doubtless supposed that a nautical almanac was simply designed for practical use at sea, and that a nautical work could be best prepared only by nautical men; to which it is sufficient to reply, that the ability to use an instrument does not necessarily imply ability to construct it. There might also have been some idea of economy in employing only those who are already in the pay of the government.

The author went on to suggest that the nautical portions might be published separately from the astronomical ephemeris, and even improved in certain aspects to make them more convenient for navigators. He closed with an expression of hope that when the subject of an ephemeris/almanac was again debated by Congress, that "the proper character of the undertaking will be duly considered" and that the nation's best astronomers, both "in the navy and out of it," would unite to produce "a truly national work, and a worthy contribution to the science of the world."

The Author of the Journal Note

The author of the *Journal* note clearly was pleading with Congress and other government authorities to permit "professional" American astronomers and mathematicians, rather than naval personnel, to take charge of the computation of the nautical almanac that was likely to be approved shortly. And he was also pleading with these "professionals" to take advantage of this opportunity to demonstrate to European

counterparts that they could produce an astronomical ephemeris more accurate than existing European publications of this type. Identifying the author of the note would certainly be useful in understanding how the community of American astronomers gradually became professionalized.

As yet, however, no documentation has been found that can enable us to attribute it with certainty to a specific individual. A close analysis of the note's contents, however, does provide some clues. The author was well aware of King's aborted attempt in June 1848 to insert in the naval appropriations bill an amendment authorizing a nautical almanac and its specific wording. He was also acquainted with the European almanacs and the tables on which they were based. And finally, if the author was aware or strongly suspected that the assumption of navigator-only use assumed by Congressional supporters of the proposed almanac had originated with Maury, the note could be interpreted as having been written not just to dispute that notion but also to suggest that someone like Maury, whom the author may have felt did not have a sufficient mathematical background to understand how an almanac/ephemeris could be calculated with an accuracy that would make it useful not only for navigators but also for astronomers, was not the proper person to superintend its computation and publication. That the author did not totally rule out the possibility that a suitable naval officer might be found suggests that he might have had some other officer in mind that he felt was better suited than Maury for this task.

The brief floor discussion surrounding King's failed 1848 attempt to insert an almanac amendment in the naval appropriations bill, including the specific wording of the amendment requiring the superintendent to be a naval officer, was reported in the *Congressional Globe*, but one can probably safely assume that this publication, like the modern-day *Congressional Record*, was read in detail by few people outside of Washington. One person who was aware of the amendment's wording even before the publication of the *Globe* report, however, was Lt. Charles Henry Davis (1807-1877), the fellow naval officer who assisted Maury in the lobbying campaign for the amendment. As Davis was most likely the person who informed the *Journal* author about the 1848 lobbying campaign for the almanac, it is worthwhile to discuss Davis's background at some length and to suggest why he may have become involved in this campaign.

The youngest son of Daniel Davis, the long-time Solicitor General of Massachusetts, Charles Henry Davis began attending Harvard College

in 1821 but suspended his formal education two years later upon securing an appointment as a midshipman in the U.S. Navy. He spent most of the first 17 years of his naval career at sea, including tours in the western Pacific Ocean (1824-1827), in the West Indies (1828), in the Mediterranean Sea (1829-1832), off the western coast of South America (1833-35), and off the coast of Brazil (1837-1840). Following the examination common at the time, he became a passed midshipman in 1829, and four years later he was promoted to lieutenant.

According to his son, Davis during his Mediterranean cruise became proficient in navigation, undertook a systematic course of reading, and obtained a knowledge of French, Spanish, and some Italian. These activities did not go unnoticed. His commanding officer at the time observed that Davis "is intelligent in his profession, energetic in his character, and devoted to the improvement of his mind. His country may anticipate much from him." Shortly after being placed on "irksome and disagreeable" receiver-ship duty in the Boston navy yard, Davis, seeking scientific activity, twice in the spring of 1833 applied for a position with the newly revived Coast Survey, but was told that it had no need at this time for an officer of his grade. During the period (1835-1837) between his next two cruises he became acquainted with Benjamin Peirce, who along with his wife and sister-in-law were already close friends with Davis's sisters. Under Peirce's tutelage, Davis now began a serious study of mathematics that ultimately led to his receiving an A.B. degree from Harvard in 1841. The close friendship that had developed between Peirce and Davis was cemented a year later when the latter married the younger sister of Peirce's wife. (The two women were the daughters of Elijah Hunt Mills, a former U.S. Senator from Massachusetts.)⁴³

With his prospects of further sea duty rather slim, given Navy customs of the time, Davis once again applied for a position with the Coast Survey, and in April 1842 was appointed an assistant at that agency. His first assignment, in 1842 and 1843, was the observation of the direction and velocity of the tides and currents in New York Bay and Long Island Sound.⁴⁴ After Alexander Dallas Bache succeeded Ferdinand Hassler as Coast Survey Superintendent in December 1843, Davis was placed in charge of the hydrography of the eastern section of the United States running from Passamaquoddy Bay (an arm of the Bay of Fundy adjoining Maine and New Brunswick, Canada, and receiving the water of the St. Croix River) to the Point Judith Light (a lighthouse marking the

western entrance to Narragansett Bay in Rhode Island). He was thus responsible for an area that included the coasts of Maine, New Hampshire, Massachusetts, and most of Rhode Island.

In the spring of 1845, Bache instructed him to begin studying the Gulf Stream. To do so, Davis and his crew aboard the brig *Washington* in the summer and fall of that year made two voyages along a cross section of this current to the southeast of Nantucket island--an investigation that initiated the first systematic oceanographic field study undertaken by the U.S. government. Among other achievements, the crew obtained a sounding and a specimen of bottom material at a depth of 1,300 fathoms and made 813 surface and subsurface temperature observations. This investigation was somewhat experimental in nature, involving the testing of new instruments and methods, and Bache, recognizing this, pointed out in his 1845 annual report that "The zeal and ability of Lieut. Com. [Lieutenant Commanding] Davis have supplied the place of experience in the modes of observation; and the methods themselves have been remarkably successful in his hands."

Davis's next assignment, in the words of one Coast Survey historian, was the "single most difficult hydrographic survey project" undertaken by the agency in the early years of Bache's superintendency. The necessity of surveying the Nantucket Shoals was pointed out to Bache in 1845 by astronomer William Mitchell, who lived on Nantucket Island: "The history of this most dangerous and fatal shoal is startling. Situated in mid-ocean; having, in low ebbs, scarcely a foot of water; in a region proverbial for its heavy swell; rising, at times, without a moment's warning; the dread of all mariners, and the grave of thousands." Compounding the problem was the large number of vessels passing through the region (between January 1842 and July 1845 Mitchell counted 569 ships, 4,469 brigs, 28,109 schooners, and 11,503 sloops passing by the Nantucket light-boat), the imprecise location of the shoals (Mitchell believed they were 20 miles north of where existing charts showed them), and their position along sea routes favored by ships engaged in the Europe-New York trade as well as those engaged in coastal trade between New York and Boston. On the last two points, Mitchell noted that "it is remarkable with what apparent recklessness vessels of the largest size (even the Atlantic steamers) dash near its parallel, from an apprehension that it is far south of them."

The difficulty of surveying this area would be well described by Bache in his 1853 annual report:

it must be surveyed with the minuteness of a harbor, without the facilities which neighboring land affords. The land cannot be seen from the deck of a vessel [situated in the vicinity of the shoals], and yet it must be traversed closely with the sounding line, and the position of the soundings be closely determined. It is necessary to establish bases from those on land by floating objects, which, like vessels, can be seen at a sufficient distance, and to preserve temporarily the positions of these floating stations by buoys. The first severe storm not only stops the actual sounding work, but is apt to break up the system entirely by removing or changing the position of these marks. The weather fit for surveying on that peculiarly stormy part of the coast is but a small fragment of each summer, and the harbors which necessarily be sought as a refuge on the coming up of storms, which cannot be weathered in such exposed situations, are distant.

For three successive summers (1846-1848), the first aboard the schooner *Gallatin*, and the latter two aboard the steamer *Bibb* obtained from the Revenue Service, Davis and his crews undertook this dangerous surveying task. Perhaps the most important result was the discovery of a "shoal, hitherto unknown, six miles to the southward of the known South Shoal, having only eight feet of water on it in some places, and lying, for a distance of nearly two miles, in an almost east and west direction." This shallow feature would ultimately be named Davis Shoal. As with the Gulf Stream work, Bache would highly praise the efforts of Davis (and others that would follow him): "It is no small source of congratulation that this difficult work is well through with, and without accident to those who have so faithfully encountered the very dangers which they seek in order to instruct others how to avoid them."

Davis took the *Bibb* out to sea one last time, in 1849, to a point about 60 miles to the east of Cape Ann. The task, successfully accomplished by him and his crew, was to locate precisely the location of White Rock (later renamed Ammen's Rock), the shoalest spot on Cashe's Ridge.⁴⁵ When Davis left the Coast Survey in July of that year, Bache did not hide the high regard that he had for Davis's character and work. To his own immediate superior, Secretary of the Treasury W. W. Meredith (the Treasury Department being the parent agency of the Survey at this time), Bache observed that:

The official reports of the progress of the Coast Survey have from time to time brought the name and services of Lieut. Davis very prominently before the Department, as marked by all the qualities which insure distinction in such a work. The loss of his services will be deeply felt. The zeal, industry, knowledge and judgment ripened by experience, which he has brought to the survey cannot soon be replaced. They have conferred upon it some of its most decided claims to usefulness and public approval.⁴⁶

And in a letter to Davis written at the same time, Bache more specifically noted that

Your name is indelibly connected with the hydrography of the coast, and with the progress of the hydrography of the Coast Survey. It will stand prominent for the elaborate work of soundings, temperatures, tides & currents executed under your immediate direction, for the hydrographical discoveries which you have made, and the beautiful charts to the materials of which you have so loyally contributed.⁴⁷

But it was not just Davis's field work that impressed Bache. Davis also advised the Survey superintendent about dealing with the Navy Department and traveled with him on trips along the coast as far south as Florida in order to attend meetings of several harbor commissions of which they were both members. Because of all these activities, "an intimacy sprung up between Bache and Davis," and the latter, according to his son, "was almost constantly in consultation with the superintendent on matters relating not only to the internal policy of the work, but in defending and supporting the institution in its relations before Congress."⁴⁸

This latter work would of course have required frequent visits by Davis to Washington, where, despite ongoing turf battles Bache and Maury, Davis may have deliberately sought the acquaintance of Maury, a fellow naval officer, if he did not already know him.⁴⁹ Undoubtedly aware, through Peirce, of Maury's earlier efforts to get an American nautical almanac authorized, Davis most likely would have involved himself in Maury's 1848 lobbying campaign because he knew that his Survey colleagues on coastal lands (and the Army's Corps of

Topographical Engineers in the interior of the country) could make use of such a publication (instead of continuing to rely on the British Nautical Almanac) for determining longitudes.⁵⁰

Whether Davis himself in late 1848 and early 1849 exerted any additional effort (either independently or in cooperation with Maury) to secure Congressional authorization of an American nautical almanac, or whether he himself aspired during this period to the superintendency of the office that might produce such an almanac, is unknown.⁵¹ But whatever may have been his job aspirations or his own views on the role of a nautical almanac at this time, his naval background would have precluded him from authoring, even anonymously, a note that generally opposed a naval officer as superintendent of the proposed nautical almanac. Davis, however, would likely have discussed the proposed 1848 amendment (and the likelihood that it would be proposed again in 1849) with various colleagues and friends, and one of them may have felt strongly enough about the proper role for the proposed almanac to author the *Journal* note.

Davis was of course in frequent contact with Bache, who, as superintendent of the Coast Survey, was certainly interested in the determination of longitudes by various methods, including the use of astronomical ephemerides. Bache had recently begun feuding with Maury over whose institution, the Coast Survey or the National Observatory, would be undertaking the task of determining with the magnetic telegraph the differences of longitude between Washington and the principal cities of the country, and thus one can easily imagine Bache having sympathy for the idea that the office that would create the proposed almanac should not necessarily be placed in the charge of a naval officer, particularly if that officer was Maury. Bache was not himself a mathematical astronomer, however, and thus he would not have had the personal acquaintance with the European almanacs (and the tables on which they were based) that was displayed by the author of the *Journal* note.

One of the few Americans at this time who was well versed in celestial mechanics was Sears Walker, who had left the National Observatory in 1847, after chafing under Maury's overbearing attitude and Navy rules, for a job with the Coast Survey, where he likely would have become acquainted with Davis. Walker, while still at the Observatory, had uncovered a predisccovery observation of the newly discovered planet Neptune made by the French astronomer Joseph-Jérôme Lalande in 1795,

and used it to calculate one of the first fairly accurate orbits of the planet. Walker's preoccupation with this work provoked Maury's rather sarcastic comment that Walker was "a much better computer than observer." Walker also conducted some of the earliest telegraphic determinations of longitude differences while employed by the Observatory and had continued such work at the Survey. Walker was certainly not on good terms with Maury by early 1849, and thus might have had a motive for advocating that Maury not be placed in charge of an almanac office (if indeed this was the intention of the author of the journal note). No evidence has yet been found, however, to indicate that Walker had any interest in the development of an American nautical almanac.⁵²

An American who at this time did have a very direct acquaintance--indeed, direct involvement--with European almanacs/ephemerides was Benjamin Apthorp Gould, Jr. (1824-1896), who, after a three-year trip to Europe, where he visited many of the leading astronomical institutions, had just returned to the United States in November 1848 with the aim of "Through perseverance and determination ... to show that I place a higher value on the true improvement of our American science than on personal comfort, salary, or reputation." He initially settled in Cambridge and likely at some point would have sought out Peirce, one of his undergraduate teachers, and, through him, he may have met Davis. (Gould and Davis may in fact have already become acquainted in the early 1840s when both were studying under Peirce at Harvard.) Gould, in fact, lobbied for the almanac superintendency in early 1849, as Dieter B. Herrmann, citing letters in German archives from Gould to Heinrich Christian Schumacher and Carl Friedrich Gauss, pointed out some years ago.⁵³ And Gould's initial letter of inquiry about such a position--a more recently discovered letter written to Maury on 12 February 1849--indicates that he had not only a direct involvement with the European almanacs, but also an awareness that such publications were used by both navigators and astronomers:

... knowing that the time must ere long come when our nation would be unwilling to depend on foreign Ephemerides to be used in our navy, marine, & observatories, [I] have during these three & a half years, devoted special attention and a great deal of time to the study of the arrangement, best methods of calculation & possible improvements of the European Almanacs, having

calculated, to a very considerable extent, for the *Berliner Jahrbuch* [the German astronomical ephemeris], and discussed the subject at full length, not only with Struve, Schumacher and Encke, the originators of the late reforms in the British and German Almanacs, but also with Bremiker, Hansen, Gauss & Jacobi.⁵⁴ I have endeavored to make myself fully acquainted with the whole system in London, Paris & Berlin & could confidently refer to any of the gentlemen whom I have mentioned.⁵⁵

Gould certainly shared the view of the *Journal* note author that American mathematicians and astronomers were capable of improving upon the accuracy of the European publications. His motive for applying for the post of “director”, he informed Maury, was that he was “persuaded, that in a short time an American Almanac might be produced, superior both to the English and to the German.” In the same letter, however, Gould indicated that he had only “a short time since” learned that an item for an American ephemeris was in the appropriation bill currently before Congress. And he betrays in this letter no awareness at this time that the 1848, and the pending, legislation authorizing a nautical almanac included wording restricting its superintendency to a naval officer. (After learning of this restriction, he complained, in a letter to Schumacher dated 30 April 1849 and cited by Herrmann, that “Our science is very full of charlatanism, so that the one with the loudest mouth is valued as the best head; also the truly distinguished minds ... lack morale courage.”) Rather than having written the *Journal* note, Gould conceivably may not have even read it prior to writing his letter to Maury.

In any case, Gould was only 24 years old at the time, he had been out of the country since 1845, and he was seeking his first professional job in the United States. The anonymous note writer, on the other hand, appears to have been an experienced mathematical astronomer who was aware not only of the contemporary state of nautical almanacs and astronomical ephemerides, but also of the state of American astronomy in general, and who strongly desired to show that the latter was on a par with European astronomy. The most likely such person would appear to be Peirce, the nation’s leading mathematician at this time. As noted earlier, he was related by marriage to Davis. The two families in fact lived across the street from each other in Cambridge, and thus Davis and Peirce would have had numerous opportunities to discuss their common interests.

Peirce, as indicated by letters from Maury cited earlier, was aware of Maury's initial efforts to get an American nautical almanac authorized, and Davis would have undoubtedly informed him about his participation in the 1848 effort.

Peirce had been interested in astronomy and especially celestial mechanics since his own undergraduate days (1825-1829) at Harvard, when Nathaniel Bowditch (the father of his Salem Private Grammar School classmate Henry Ingersoll Bowditch) enlisted him to read the proof sheets of his translation of Pierre Laplace's *Traité de mécanique céleste* and suggest revisions and corrections. In 1840 Peirce published *An Elementary Treatise on Plane and Spherical Trigonometry, ... Particularly Adapted to Explaining the Construction of Bowditch's Navigator and the Nautical Almanac*. His 1843 he gave a series of public lectures in Boston on the great comet that appeared that year, and four years later published a list of known orbits of comets in the ten-volume *American Almanac and Repository of Useful Knowledge*, for which he had prepared the mathematical section.⁵⁶

Soon after the discovery of Neptune in 1846 Peirce began working with Walker, an old friend, to compute the perturbations of Neptune on Uranus. This work led to Peirce's conclusion that Neptune was not the planet that had been theoretically predicted by Urbain Jean Joseph Le Verrier (and by the British mathematician John Couch Adams), a thesis that the French mathematician criticized in a letter to Maury that the latter arranged to have published in both the *National Intelligencer* newspaper and Ormsby MacKnight Mitchel's popular-level *Sidereal Messenger* astronomical periodical. Among other things, Le Verrier claimed that Mitchell and Peirce "speak of things they have not read." Peirce defended his work in a subsequent issue of the latter, but the fact that Maury, by publishing Le Verrier's letter, had forced him to participate in a scientific debate in public may have left a bitter taste. Peirce also may have come away from the Neptune episode with the feeling that Europeans did not take American astronomy seriously.⁵⁷

One can easily imagine that by early 1849, Peirce could have developed a strong interest in the authorization of an American astronomical ephemeris, seeing it as a means of showcasing the abilities of American mathematicians and astronomers. And given Maury's denigration of Walker's abilities as an astronomer,⁵⁸ Peirce by this time may have concluded that Maury was not the person to be given the

“general direction” of the proposed almanac (as the latter had envisioned in his 1847 letter to Adams). All of these suppositions, if true, suggest that Peirce was the most likely author of the anonymous note that appeared in the January 1849 issue of *The American Journal of Science and Arts*.

The Appointment of Davis as Superintendent

On 4 March 1849, the day after the naval appropriations bill containing the appropriation for an American-made nautical almanac was passed by Congress (with the restriction that its superintendent had to be a naval officer still intact), the Whig administration of Zachary Taylor took over from the Democratic administration of President James Polk. Thus it was a new Secretary of the Navy, William Ballard Preston, who had the responsibility for appointing the first superintendent of the office that would produce the almanac. The person chosen would of course have the most power to define the role that the almanac would carve out in the coming years. Preston had just completed a single term as a Congressman from Virginia, the state where Maury had spent most of his adult life while on shore. While it is unknown who Preston may have consulted in regarding the Almanac appointment, one could easily imagine that he would have sought the advice of Maury, a fellow Virginian, the head of the navy’s observatory, and the person who had championed the concept of an American nautical almanac. Thus it would not be surprising that it was Maury who suggested to Preston that he consider Davis, who not only had assisted him in the 1848 attempt to get the almanac authorized, but also was probably one of the few naval officers that had a mathematical background that would be extremely helpful in managing the computations that would have to be undertaken for the Almanac’s various tables.

Maury, however, may not have anticipated the program of action that Davis proposed soon after being briefly interviewed by Preston on 26 March. Davis, as requested, addressed a letter five days later to the Navy Secretary, stating his views on the conduct of the newly authorized American Nautical Almanac and the duties of the superintendent. Davis’s letter to Preston indicates that he was certainly in agreement with the anonymous *Journal* author regarding the desirability to produce an ephemeris that would be useful not only for navigators, but also for astronomers:

The practical end of this work will be to supply the navigator with the elements required for determining his geographical position at sea by means of astronomical objects; its purpose in science is to predict for the astronomer the exact times and places of the principal heavenly bodies, used by him in his observations and computations.

The first of these objects is already accomplished by the British Nautical Almanac, and though it may be a matter of proper national pride to be independent in this, as in all other commercial respects, yet our practical wants are now so perfectly supplied, that if this motive alone for publishing an American Almanac existed, it would hardly be considered sufficient to justify the necessary labor and expense.

But an opportunity is now offered to the astronomers and men of science in this country, under the patronage of the Navy Department, to promote the cause of sound knowledge and to extend the national usefulness and honor by preparing an ephemeris based upon calculations, which shall be more perfect than those at present employed.⁵⁹

After explaining that the positions of the heavenly bodies predicted in an ephemeris resulted from a mathematical theory derived from the known laws of motion and a study and comparison of numerous observations, Davis then pointed out that the theories presently used in other almanacs were deduced from observations made in the 18th century and the earliest part of the 19th century. By taking into account all the observations made since then, Davis argued, the theories of the sun, the moon, and all the planets "would be improved, the predictions of the Almanac be rendered more precise, and the labors of the observer and computer be made more satisfactory."

Davis made it clear that such a revision could not "be done by our own naval officers," as Maury, Secretary of the Navy Mason, and Maury's Congressional friends had believed, but rather should be carried out by professional astronomers and mathematicians, whom he was confident would be quite willing to undertake such a project:

I need not say to you that a work so comprehensive, so laborious, and so profound, is suited to engage the sympathy and hearty cooperation of men of learning in this country and

throughout the world. In subordination to the highest aims of humanity, it addresses itself to patriotic, as well as professional ambition, and its judicious and competent management involves so much national responsibility, that all care may well be taken to ensure a performance worthy of the undertaking.

Davis promised that if charged with the superintendency of the Almanac office, he would consult the most eminent American astronomers and mathematicians for their opinions on the content of the work, as well as their possible assistance in producing it. Preston was apparently impressed by Davis's proposals, as an annotation by the Secretary on Davis's letter indicates that he issued an order, carried out on 7 April, for Davis to hold himself in readiness for the position. Sometime during the spring of 1849 Davis likely informed Preston of his desire to set up the Nautical Almanac office in Cambridge, where he had lived, while on shore, for the past 14 years; where he could consult with Peirce, whom he intended to appoint as his chief scientific advisor; and where he could make use of the books in the Harvard University library.

Maury apparently eventually learned of Davis's stated intention to use all available observations, not just ones made in the United States, in producing the nautical almanac--a plan that Maury viewed to be at variance with his own conception of such a publication. Maury, it may be recalled, had argued in the mid-1840s that the production of a nautical almanac based on American observations, especially those made at his observatory, was essential to justify continuing Congressional support for his facility. He expressed his concerns in a letter to Secretary Preston on 9 July 1849, eight days after the beginning of the new fiscal year, when the nautical almanac authorized by Congress became official:

As many of the materials, in the shape of data, proper to be used in the calculations, for the American Nautical Almanac, are to be found among the observations & determinations which have already been made & which will continue to be made at this Observatory & as a Nautical Almanac is looked upon, as among the most precious of the many valuable fruits of a National Observatory, I beg leave respectfully to request that this connexion between the Observatory & the Almanac, be recognized in your instruction to the Officer who may be charged with the superintendence of the Almanac & further, that he be required, in

order to make the work as American as possible, to consult the results of the Observatory & in all cases to give to the data, which may be found there, preference over like data from foreign sources.⁶⁰

Maury, unlike the *Journal* writer and Davis, was seemingly unconcerned about producing an ephemeris more accurate than European ones. Rather, as he told Preston, "I desire to see the principle recognized & established of having the Nautical Almanac a work as thoroughly American as our means will allow it to be." Maury may also have already begun to sense that Davis was plotting a more independent course of action for the Almanac office than he (Maury) had envisioned. The latter, it may be recalled, had assumed, in his 1847 letter to Adams, that the Nautical Almanac Office superintendent would be subordinate to him.⁶¹

Two days after Maury's letter, Preston issued an order detaching Davis from the Coast Survey and formally charging him with the duty of superintending the office that would prepare the almanac.⁶² Upon receiving his new orders, Davis traveled from Cambridge to Washington and met with Preston on 29 July. At that meeting, according to Davis, the Navy secretary expressed his desire that the newly approved almanac

should (without designing to introduce any invidious national distinctions into science) be essentially the product of our own thought & labor, that it should be worthy to stand as an exponent of American science, and that it should be honourable to that branch of the public service [the Navy department], to which the duty of preparing it for publication has been assigned by Congress.⁶³

The first objective was undoubtedly stated by Preston at the behest of Maury. In a letter to Preston two days later, Davis promised that he would make use of the National Observatory's observations "to the utmost extent of their utility," but he made it clear that they could play only a limited role in the construction of the highly accurate ephemeris that he envisioned. He explained to Preston that

Our National Observatory must have existed a half century before it will be able to furnish independent observations sufficient for a

determination of a correct theory of the moon or primary planets. But these theories are already calculated from, and our tables of computation are based upon, the observations begun long since and uninterruptedly continued at the old established observatories of Europe.⁶⁴

In effect, Davis, without directly criticizing his fellow naval officer, was pointing out to Preston that Maury's vision of an almanac based solely on a mere five years of observations at the National Observatory would, if carried out, not produce a very accurate ephemeris. For the initial years of its publication, Davis admitted, the American almanac, in order to be accurate enough to be of use to navigators and astronomers, would of necessity have to rely at least partially on existing European-made tables of computation based on European observations.

But Davis entirely agreed with the objective of making the almanac "stand as an exponent of American science," and he had, since his initial interview with Preston in March, clearly given much thought as to how it could be attained. On the day after his meeting with Preston in July, he sent no less than four letters detailing in writing a plan of action that "has been matured with deliberation and consultation" and that he had already verbally discussed with Preston.

Davis reminded Preston that in March he had expressed his desire to have the new almanac's tables be based on improved theories of the motions of the Sun, the Moon, and the planet "in order to make the work worthy of the advanced state of modern science, and to render it altogether creditable and useful as an American production." Davis now informed the Secretary of his intention to invite "the most eminent mathematicians & physicists in the country" to produce new theories of the motions of the planets. He proposed offering amounts ranging from \$200 to \$500, depending on the size of the work, to, among others, Peirce; Gould; Lewis Reeve Gibbes (1810-1894), professor of mathematics, astronomy, and chemistry at the College of Charleston in South Carolina since 1838; Edward Henry Courtenay (1803-1853) of the University of Virginia; Stephen Alexander (1806-1883), professor of mathematics (1834-1840) and then of astronomy (since 1840) at the College of New Jersey (now Princeton University); John Downes (1799-1882) of Philadelphia; Elias Loomis (1811-1889), professor at the University of the City of New York; H. J. Anderson formerly of Columbia College; Theodore Strong (1790-1869), professor of mathematics at Rutgers College since 1827; William

Holmes Chambers Bartlett (1804-1893), professor of natural and experimental philosophy at the U.S. Military Academy since 1836; and John Huntington Crane Coffin (1815-1890) and Joseph Stillman Hubbard (1823-1863), professors of mathematics at the National Observatory since 1845. Davis warned Preston that it was likely that some of these gentleman would not be able to accept his offers and those that did would probably be unable to complete their assignments before the close (on 30 June 1850) of the current fiscal year. (Davis's realistic assessment of his chances of securing the services of all these gentlemen proved to be prophetic. In addition to Peirce, who was appointed the consulting astronomer to the Nautical Almanac Office, Davis was able to hire or contract with only Gould, Loomis, and Downes among the above for work in developing the first edition of the *American Ephemeris and Nautical Almanac*, which appeared in 1852 for the year 1855.)

But in the quest for the most accurate ephemeris, Davis, unlike Maury, was willing to go beyond the borders of the United States. He had learned that Le Verrier had produced a new theory of the motion of the planet Mercury that was "immediately available for the computation of the necessary tables," and that the German theoretical astronomer Peter Andreas Hansen (the director since 1825 of the private observatory of the duke of Mecklenburg at Seeberg, near Gotha) was currently preparing a new set of lunar and solar tables to be ready in about a year. Davis recommended that the Navy Department offer to purchase the use of Hansen's theory or tables in order "to acknowledge the value of his contribution to astronomical science."

Davis acknowledged that waiting for Hansen's lunar and solar tables and the preparation of new planetary tables would necessarily delay the appearance of the first edition of the new almanac. The alternative, however, was unacceptable:

to compute an almanac from the old tables exclusively, would be only to reproduce, on this [side] of the Atlantic, the European works, without change or improvement, while we should be compelled to adopt, (not without trouble,) into our system the tables of Hansen when published, & such other improvements as might gradually appear.

Perhaps anticipating that an impatient Congress might not be happy with a publication postponement, Davis observed that which would be

“intrinsically and permanently valuable” in a nautical almanac, as in all other literary and scientific productions could only be achieved at the expense of time and labor.⁶⁵

Conclusion

Maury's advocacy for a separately produced American nautical almanac was clearly prompted by his general desire to free American ships, both naval and maritime, from dependence on foreign-produced products, such as coastal charts and almanacs, for helping them navigate both along the coasts and in the open sea. It was a justification that certain politicians, especially those on the House Naval Affairs Committee and in the Whig Party, found appealing, and which likely was the primary influence in enabling an almanac to be authorized in the Whig-dominated 30th Congress that was in session in early 1849.

By that year, however, the developing American astronomical community was reaching a critical point. Numerous observatories had been built in the previous two decades, and astronomers were also being employed in increasing numbers for surveying the coasts and the unexplored land in the western regions of the country.⁶⁶ And in the late 1840s debate over determining whether the newly discovered planet Neptune was the one that had been theoretically predicted by Le Verrier, certain members of the American astronomical community began feeling that they could speak with their European counterparts on nearly equal terms.

The author (be it Peirce or someone else) of the anonymous note in the January 1849 issue of *The American Journal of Science and Arts* certainly shared this view and envisioned that an American-produced astronomical ephemeris, more accurate than those currently being produced in Europe, would be an ideal showcase for demonstrating the abilities of American astronomers. Such a level of accuracy could be achieved, in the author's view, only if the person placed in charge of preparing such an ephemeris had a good knowledge of mathematical astronomy and the ability to work harmoniously with those who would be developing the theories of motion of the various astronomical bodies and computing the tables that would actually appear in the ephemeris. One cannot help but suspect that the author felt that if Maury, who by now was having increasing difficulty working with other members of the American scientific community, was placed in charge of the almanac/ephemeris that

he had long advocated and that seemed to be on the verge of being authorized, its accuracy would not be at the desired level.

The subsequent development of the *American Ephemeris and Nautical Almanac* is beyond the scope of this article and is covered in other articles appearing in this volume, but enough has been said here to indicate that Davis, the person appointed as the first superintendent of the Nautical Almanac Office, clearly agreed with the goal of high accuracy expressed by the anonymous author and that his initial actions were taken with this goal in mind. Davis would in fact establish the environment that would permit Peirce, Simon Newcomb, George W. Hill, Wallace Eckert, and others in the next 150 years to seek and achieve the high level of accuracy that is the best measure of the usefulness of an almanac/ephemeris.

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NOTES

1 For a more detailed history of the depot, later to become the U.S. Naval Observatory, see Steven J. Dick, "How the U.S. Naval Observatory Began, 1830-65," *Sky & Telescope*, **60**, no. 6 (Dec. 1980), 466-71, which is reprinted with reference notes in Steven J. Dick and LeRoy E. Doggett (eds.), *Sky with Ocean Joined: Proceedings of the Sesquicentennial Symposia of the U.S. Naval Observatory, December 5 and 8, 1980*

(Washington: U.S. Naval Observatory, 1983), pp. 166-81; Jan K. Herman and Elizabeth J. Miller, *Lighthouse of the Sky: The U.S. Naval Observatory 1844-1893* (Washington: National Academy of Sciences, [1983]); Jan K. Herman, *A Hilltop in Foggy Bottom: Home of the Old Naval Observatory and the Navy Medical Department* (Washington: Naval Medical Command, Department of the Navy, 1984); and two other papers by Dick, "John Quincy Adams, the Smithsonian Bequest and the Founding of the U.S. Naval Observatory," *Journal for the History of Astronomy*, **22**, pt. 1 (Feb. 1991), 31-44, and "Centralizing Navigational Technology in America: The U.S. Navy's Depot of Charts and Instruments, 1830-1842," *Technology and Culture*, **33**, no. 3 (July 1992), 467-509.

2 Gilliss to Elias Loomis, 4 July 1843, in Nathan Reingold (ed.), *Science in Nineteenth-Century America: A Documentary History* (New York: Hill and Wang, 1964), p. 137.

3 Gilliss to Loomis, 18 October 1844, in Reingold, *Science in Nineteenth-Century America*, p. 138.

4 Between 1838 and 1842 Maury wrote under a pseudonym a series of articles on naval reform for the Richmond (Va.) *Whig and Public Advertiser* newspaper and the *Southern Literary Messenger* magazine; in July 1841 the magazine revealed that Maury was the author. For a discussion of these articles, see Frances Leigh Williams, *Matthew Fontaine Maury Scientist of the Sea* (New Brunswick, N.J.: Rutgers University Press, 1963), esp. chapter 7 (Campaign for Naval Reform).

5 In his entry on "Thomas Butler King" in the *Dictionary of American Biography*, vol. 10, p. 403, E. Merton Coulter wrote that King, a Georgia congressman (1839-1843, 1845-1850) and a chairman of the House Naval Affairs Committee "promoted the founding of the National Observatory in Washington and the appointment of Matthew F. Maury to direct it." Because King was out of office when Maury was appointed superintendent of the depot in 1844, Coulter was likely referring to Maury's appointment to the temporary depot in 1842. It is not clear, however, on what documentation Coulter based his statement.

6 Maury to Crane, 7 November 1844, copy transcribed in ledger-book in the National Archives (NA), Record Group (RG) 78, Entry 1, Vol. 1, pp. 297-99.

7 Regarding Maury's work in this area, see Williams, *Matthew Fontaine Maury*, pp. 148-54 and 178-95 (Chapter X - Charting the Winds and Currents of the Sea).

8 Regarding Maury's tours of sea duty, see Williams, *Matthew Fontaine Maury*, pp. 43-100.

9 Williams, *Matthew Fontaine Maury*, pp. 103 and 157.

10 For a discussion of the various methods for determining one's longitude by astronomical means, see Appendix I (pp. 194-198) of Derek Howse's *Greenwich Time and the Discovery of Longitude* (Oxford: Oxford University Press, 1980).

11 Harold R. Burstyn, *At the Sign of the Quadrant: An Account of the Contributions to American Hydrography made by Edmund March Blunt and his Sons* (Mystic, Connecticut: The Marine Historical Association, Inc., 1957), p. 33.

12 Maury to E. & G. W. Blunt, letters of 29 Sept. and 5, 9, and 16 Oct. 1843 and 26 Oct. and 4 Nov. 1844, NA, RG 78, Entry 1, Vol. 1, pp. 123-24, 133, 136, 144, 288, and 294.

13 Maury to Mason, 18 November 1844, NA, RG 78, Entry 1, Vol. 1, pp. 309-10.

14 Mason, "Report of the Secretary of the Navy," p. 525 in Message from the President of the United States, to the Two Houses of Congress, at the Commencement of the Second Session of the Twenty-Eighth Congress, 28th Cong., 2nd Sess., 1844, House Ex. Doc. No. 1.

15 J.R. Ingersoll, "National Institute," *The American Review*, 2 (Sept. 1845), 238.

16 Maury to Crane, 20 Oct. 1845, in Message from the President of the United States, to the Two Houses of Congress, at the Commencement of the First Session of the Twenty-Ninth Congress, 29th Cong., 1st Sess., 1845, House Ex. Doc. No. 1, pp. 689-91.

17 Maury to Peirce, 9 Sept. 1845, Maury file, Peirce Papers, Houghton Library, Harvard Univ. (original); NA, RG 78, Entry 1, Vol. 2, pp. 6-7 (copy). Maury was referring to tables of refraction that the Prussian astronomer Friedrich Wilhelm Bessel had derived from his reduction of the observations of English Astronomer Royal James Bradley. For this work Bessel was awarded the Lalande Prize of the Institut de France in 1811.

18 Maury to Peirce, 27 Dec. 1845, Maury file, Peirce Papers, Houghton Library, Harvard Univ. (original); NA, RG 78, Entry 1, Vol. 2, pp. 64-67 (copy).

19 Maury to Peirce, 16 Jan. 1846, Maury file, Peirce Papers, Houghton Library, Harvard Univ.

20 Maury to Holmes, 7 Feb. 1846, NA, RG 78, Entry 1, Vol. 2, pp. 81-82.

21 Wendell H. Stephenson. "Stanton, Frederick Perry" article, *Dictionary of American Biography*, vol. 17, pp. 523-24; Buchanan to Howell Cobb, 29 Dec. 1849, in Ulrich Bonnell Phillips (ed.), *The Correspondence of Robert Toombs, Alexander H. Stephens, and Howell Cobb* (New York: Da Capo Press, 1970), p. 181.

22 According to George B. Galloway, *History of the House of Representatives* (New York: Thomas Y. Crowell Company, 1961), p. 296, the 27th Congress, which approved the new depot/observatory, was composed of 132 Whigs, 103 Democrats, and 6 men affiliated with other parties, and had one seat vacant, while the 29th Congress was composed of 78 Whigs, 141 Democrats, and 6 men affiliated with other parties.

23 "Naval Appropriations Bill" debate, 29th Cong., 1st Sess., 11 June 1846, *Congressional Globe*, vol. 15, pp. 961-63.

24 "Nautical Almanac" vote, 29th Cong., 1st Sess., 15 June 1846, *Congressional Globe*, vol. 15, p. 975.

25 The above analysis of the almanac vote is based on party affiliations provided in the *Biographical Directory of the American Congress 1774-1961* (Washington: Government Printing Office, 1961).

26 Mason, "Report of the Secretary of the Navy," 5 Dec. 1846, p. 385 in Message from the President of the United States, to the Two Houses of Congress, at the Commencement of the Second Session of the Twenty-Ninth Congress, 29th Cong., 2nd Sess., 1846, Senate Ex. Doc. No. 1.

27 According to Galloway (ref. 22), the 30th Congress was composed of 115 Whigs, 108 Democrats, and 4 men affiliated with other parties.

28 Maury to Adams, 17 Nov. 1847, published as "National Observatory," *The Southern Literary Messenger*, Jan. 1848, pp. 4-10, esp. p. 9.

29 Mason, "Report of the Secretary of the Navy," 6 Dec. 1847, p. 956 in Message from the President of the United States, to the Two Houses of Congress, at the Commencement of the First Session of the Thirtieth Congress, 30th Cong., 1st Sess., 1847, Senate Ex. Doc. No. 1.

30 Davis to Maury, 21 March 1848, NA, RG 78, Entry 7, Box 3. The original letter, like many others to Maury dating from this period, is badly faded, but a photographic enhancement of it, made for unknown reasons in 1958, has made it possible to read most of its contents. In the letter, Davis recollects, as apparently Maury had not, most of the wording of the amendment, indicating that he [Davis] either played a role in its drafting, or had at least seen the draft before it was transmitted to King. Why Davis may have been involved in this attempt to get the almanac approved is discussed later in this paper.

31 "Appropriations for Naval Service" debate, 30th Cong., 1st Sess., 15 June 1848, *Congressional Globe*, vol. 17, p. 841.

32 Maury to Warrington, 28 Oct. 1848, NA, RG 78, Entry 1, Volume 3, pp. 376-80 and 388; Warrington to Mason, "Report from the Bureau of Ordnance and Hydrography," 1 Nov. 1848, and Mason, "Report of the Secretary of Navy" both in *Message from the President of the United States, to the Two Houses of Congress, at the Commencement of the Second Session of the Thirtieth Congress*, 30th Cong., 2nd Sess., 1848, House Ex. Doc. No. 1, pp. 614-15, 733, and 737.

33 "Naval Appropriations Bill" debate, 30th Cong., 2nd Sess., 1 Feb. 1849, *Congressional Globe*, vol. 18, p. 428.

- 34 Stanton to Maury, 4 Feb. 1849, NA, RG 78, Entry 7, Box 4, folio 168.
- 35 "Some Remarks Upon an American Nautical Almanac," *The American Journal of Science and Arts*, 2nd series, 7 (January 1849), 123-25.
- 36 The development of astronomy in the United States during the first half of the 19th century, which included the founding of 25 observatories between 1828 and 1852, is discussed by David F. Musto in "A Survey of the American Observatory Movement, 1800-1850," *Vistas in Astronomy*, 9 (1967), 87-92.
- 37 For an extensive discussion of the work of Walker and Peirce on the orbit of Neptune, see John G. Hubble and Robert W. Smith, "Neptune in America: Negotiating a Discovery," *Journal for the History of Astronomy*, 23, no. 4 (November 1992), 261-291.
- 38 For a detailed description of the ephemerides used in the British Nautical Almanac from 1767 to 1900, see J. Weeks, "Historical information" (Chapter 13, pp. 609-665) in P. Kenneth Seidelman (ed.), *Explanatory Supplement to the Astronomical Almanac* (Mill Valley, Calif.: University Science Books, 1992).
- 39 Francesco Carlini, "Nuove tavole dei moti apparenti del sole pel meridiano di Milano : calcolate sui più moderni elementi." in *Efemeridi astronomiche di Milano per l'anno 1833* (Milano : Dalla Regia Stamperia, 1832).
- 40 Johann Karl Burckhardt, *Tables de la lune* (Paris: Courcier, 1812). In 1834, the British Nautical Almanac began using a revised form of Burckhardt's tables that had been corrected for nutation; this probably explains the 1834 date cited by the author.
- 41 Bernhardo de Lindenau, *Tabulae Veneris novae et correctae: ex theoria gravitatis clarissimi de Laplace et ex Observationibus recentissimis in specula astronomica Seebergensi habitis erutae* (Gotha: Libraria Beckeriana, 1810); *Tabulae Martis: novae et correctae ex theoria gravitatis clarissimi de Laplace et ex observationibus recentissimis erutae* (Eisenberg: Libraria Schoeniana, 1811); and *Investigatio nova orbitae a Mercurio circa solem descriptae; accedunt tabulis planetae ex elementis*

recens repertis et theoria gravitatis illustr. de Laplace constructae (Gotha: Libraria Beckeriana, 1813).

42 A. Bouvard, *Tables de Jupiter, de Saturne et d'Uranus, construites d'après la théorie de la mécanique céleste* (Paris: Bachelier et Huzard, 1821).

43 The most detailed description of Davis's early naval career, from which this account is derived, is to be found in the first four chapters of his son Captain Charles H. Davis, Jr.'s *Life of Charles Henry Davis Rear Admiral 1807-1877* (Boston and New York: Houghton, Mifflin and Company, 1899). Shorter accounts of the senior Davis's life and career include C. H. Davis, Jr., "Memoir of Charles Henry Davis. 1807-1877," *National Academy of Sciences Biographical Memoirs*, **4** (1902), 23-55; anonymous, "Charles Henry Davis," *Proceedings of the American Academy of Arts and Sciences*, **12** (1876-1877), 313-321; Allen Wescott, "Davis, Charles Henry," *Dictionary of American Biography*, vol. 5, pp. 106-107; and Don Groves, "The Unsung Sailor of Science," *Naval Engineers Journal*, **81** (October 1969), 27-34.

44 This work, according to his son, initiated a general study by Davis of the laws of tidal action and two publications by him: "Upon the Geological Action of the Tidal and Other Currents of the Ocean," *Memoirs of the American Academy of Arts and Sciences*, new series, **4** (1849), 117-156; and "On the Law of the Deposit of the Flood Tide," *Smithsonian Contributions to Knowledge*, **3** (1852).

45 For the most detailed discussion of Davis's work for the Coast Survey, from which this account is derived, see the section "Bache's Early Years" of Albert E. Theberge's *The Coast Survey 1807-1867: Volume I of the History of the Commissioned Corps of the National Oceanic and Atmospheric Administration* (1998), a document that is available on-line at <http://www.lib.noaa.gov/edocs/TITLE.htm>). Theberge is a retired captain in the NOAA Corps.

46 Bache to Meredith, 17 July 1849, copy transcribed in NA, RG 78, Entry 24, Box 1 [Binder 1], folio 6.

47 Bache to Davis, 17 July 1849, copy transcribed in NA, microfilm roll 32, vol. 4, folio 597.

48 Hugh Richard Slotten, *Patronage, Practice, and the Culture of American Science: Alexander Dallas Bache and the U.S. Coast Survey* (New York: Cambridge University Press, 1994), p. 83; Davis, Jr., *Life of Charles Henry Davis*, p. 84. The most public defense of the Survey that the senior Davis made was in early 1849 in response to a bitter attack on the Survey made (initially anonymously) by James Ferguson, a former first assistant of the Survey whom Bache had dismissed because of questionable measurements that Ferguson had made. See "Survey of the Coast of the United States," *Hunt's Merchant Magazine and Commercial Review*, **20**, no. 2 (February 1849), 131-149; Davis, "The Coast Survey of the United States," *ibid.*, no. 4 (April 1849), 402-414; and Ferguson, "The Coast Survey of the United States," *ibid.*, no. 6 (June 1849), 592-603. Davis's response was also published separately as a pamphlet: *Response to an Article in the February Number of Hunt's Merchant Magazine on the Coast Survey of the United States* (New York: Press of Hunt's Merchant Magazine, 1849).

49 The sea duties of Maury and Davis (see refs. 8 and 43) had each included tours of duty aboard the sloop-of-war *Vincennes*, but at different times (Maury from 1827 to 1830 and Davis from 1833 to 1834). They had also served separate tours aboard the schooner *Dolphin* (Davis from 1824 to 1826 and Maury briefly in 1833). In January 1827, however, their respective ships at the time (Davis on the frigate *United States* and Maury on the frigate *Brandywine*) were simultaneously in the harbor of Valparaiso, and the two then-midshipmen may have initially met during this period.

50 Davis wrote a detailed description of the Coast Survey's operations in triangulation, astronomical and magnetic observations, topography, and hydrography in his pamphlet *The Coast Survey of the United States* (Cambridge, Mass.: Metcalf and Company, 1849). This pamphlet was most likely a reprint of an article with the same title (which I have not seen) that Davis published in the 1848 volume (pp. 65-82) of the *American Almanac*.

51 An unequivocal, but undocumented, claim that Davis played a major role in the advocacy of the almanac was made by Simon Newcomb, who, in *The Reminiscences of an Astronomer* (Boston and New York:

Houghton, Mifflin and Company, 1903, p. 63), stated that Davis was “a leader and moving spirit in securing the appropriation” for the almanac. Similar claims appear to have been made by other individuals. Davis’s son wrote that “the work of the coast survey had brought out very clearly the necessity for a national ephemeris, which should take the place of and improve upon the ‘British Nautical Almanac;’ and Davis threw the whole weight of his influence and energy into the accomplishment of this purpose” (p. 86 of *Life of Charles Henry Davis*). Harold L. Burstyn, like the younger Davis apparently completely unaware of Maury’s advocacy for an almanac, characterized Davis as “presumably the prime mover behind the new agency” in his “Seafaring and the Emergence of American Science,” pp. 76-109, esp. p. 99, in *The Atlantic World of Robert G. Albion*, ed. by Benjamin W. Labaree (Middletown, Conn.: Wesleyan University Press, 1975). It is not clear, however, whether the statements of the younger Davis and Burstyn refer to preauthorization advocacy for or postauthorization development of an American nautical almanac, and neither author cites any documentation to support specifically a significant role for the elder Davis in the preauthorization advocacy effort.

52 On Walker’s difficult working relationship with Maury, see Marc Rothenberg, “Observers and Theoreticians: Astronomy at the Naval Observatory, 1845-1861,” pp. 29-43, esp. p. 37, in *Sky with Ocean Joined: Proceedings of the Sesquicentennial Symposium of the U.S. Naval Observatory December 5 and 8, 1980* (Washington: U.S. Naval Observatory, 1983), and the section “Bache and Maury--The Attack of 1849” in Theberge, *The Coast Survey* (ref. 45).

53 D.B. Herrmann, “B.A. Gould and his *Astronomical Journal*,” *Journal for the History of Astronomy*, 2 (June 1971), 98-108, esp. p. 101. Schumacher (1780-1850) directed an observatory in Altona and was the founder and first editor (1823-1850) of the *Astronomische Nachrichten*. He published astronomical ephemerides and auxiliary tables between 1820 and 1829. Gauss (1777-1855), one of the major mathematicians of all time, made contributions not only to pure mathematics, but also to many mathematical sciences.

54 The German-born astronomer Friedrich Georg Wilhelm Struve (1793-1864) was at this time director of the Pulkovo observatory; Gould may

have corresponded with him, rather than meeting with him in person. The German astronomer Johann Franz Encke (1791-1865) directed the Berlin observatory beginning in 1825 and edited the *Berliner astronomisches Jahrbuch* yearbooks for 1830-1866. The German astronomer and mathematician Carl Bremiker (1804-1877), working at the royal observatory in Berlin and later (beginning in 1868) at the Prussian Geodetic Institute, made observations from 1841 to 1859 for the *Berliner akademischen Sternkarten* (a series of celestial atlases), took part in the calculations for the *Berliner astronomische Jahrbuch*, and from 1850 to 1877 edited the *Nautische Jahrbuch*. The German mathematician Carl Gustav Jacob Jacobi (1804-1851) was a professor of mathematics at the University of Berlin. His contributions to mathematical physics do not appear to include anything dealing with astronomy, and Gould's reason for mentioning him in his letter are unclear. Peter Andreas Hansen is discussed in the text near the end of this paper.

55 Gould to Maury, 12 Feb. 1849, NA, RG 78, Entry 7, Box 6. The letter is actually misdated "February 12th 1848," but Gould was still in Europe at that date, and the letter clearly indicates that he was back in the United States at the time the letter was written.

56 For further biographical information on Peirce, see R. C. Archibald, "Peirce, Benjamin," *Dictionary of American Biography*, vol. 14 (1934), pp. 393-397, and Carolyn Eisele, "Peirce, Benjamin Osgood," *Dictionary of Scientific Biography*, vol. 10 (1974), 478-481.

57 While Hubbell and Smith discuss the concern of other Americans in the late 1840s regarding the subordinate state of American science vis-à-vis European science and the role that Peirce's conflict with Le Verrier might play in shaping European perceptions on this matter, their account (ref. 37) does not leave a clear idea of how defensive Peirce himself may have been concerning American astronomy at this time.

58 Rothenberg (ref. 52) cites Maury's letter to Peirce dated 26 Jan. 1846 in which the former stated that "I can boast assistants here in no whit his [Walker's] inferiors."

59 Davis to Preston, 31 Mar. 1849, NA, RG 45, vol. 3, folio 195 (now on Microcopy No. 148 [Letters Received by the Secretary of the Navy from

Officers Below the Rank of Commander 1802-1884], Roll 188). Davis had a copy of the letter transcribed into a ledger-book now preserved in the Library of Congress Manuscript Division (LCMD), Naval Historical Foundation Collections (NHFC), The Records of the U.S. Naval Observatory (RUSNO), Container 15, "Nautical Almanac - Correspondence (Outgoing) May 1849-July 1852" folder, folios 1-3. Another ledger-book containing copies of Davis's outgoing letters was donated by Davis to Harvard University in 1860 and is now in its Houghton Library.

60 Maury to Preston, 9 July 1849, NA, RG 78, Entry 1, Volume 4, p. 209.

61 Davis's plan to locate the Nautical Almanac Office in Cambridge rather than Washington may also have rankled Maury. Five months later, the latter asked Davis "Are you sure you are acting wisely in not making your head quarters in Washington? I ask because I heard some one say - not the sec. however - that the sec^y. oug[ht] not look upon the Almanac as a permanent affair - That it belongs to no Bureau, and that therefore it is not regarded as belonging to the Navy proper - in connection with this idea, see his Report. - This is all that induced me to ask the question. I presume you have thought over the matter and that you feel that its all right as it is." (Maury to Davis, 2 January 1850, NA, RG 78, Entry 1, Volume 4, pp. 437-438.) One cannot help but wonder if it was actually Maury himself who was questioning the physical separation of the Nautical Almanac Office from the National Observatory.

62 Preston to Davis, 11 July 1849, LCMD, NHFC, RUSNO, Container 23, "Nautical Almanac Office - Correspondence - Navy Department (Incoming) 1849-1852" folder, folio 4.

63 Davis to Preston, 30 July 1849, LCMD, NHFC, RUSNO, Container 15, "Nautical Almanac - Correspondence (Outgoing) May 1849-July 1852" folder, folios 4-6.

64 Davis to Preston, 31 July 1849, in *American Prime Meridian*, H. Miscellaneous Doc. No. 286, 31st Congress, 1st Session, 1850, pp. 2-7, esp. p. 6. Davis wrote this letter to justify his proposal for an American prime meridian, but the passage cited appears to have been a response to

Maury's pleadings that the new almanac to be based almost entirely on the observations of the latter's observatory.

65 Davis was ultimately forced to publish the first edition of the almanac (in 1852 for the year 1855) without using the work of either Le Verrier or Hansen. The latter's *Tables de la lune construites d'après le principe newtonien de la gravitation universelle* would not be published until 1857. They were, on the other hand, so accurate that George Airy, the British Astronomer Royal, was moved to proclaim that "Probably in no recorded instance has practical science ever advanced so far by a single stride." Two additional years would pass before Le Verrier's "Théorie du mouvement de Mercure" would appear in vol. 5 of the *Annales de l'Observatoire impérial de Paris*.

66 Regarding the methods used by civilian surveyors and the Army Corps of Topographical Engineers to determine latitudes and longitudes in the western interior regions of the country, see Harland G. Tompkins, "Early Trail Explorers Had Stars in Their Eyes," *Overland Journal*, 8, no. 4 (1990), and Rollie Schafer, "Finding the Way and Fixing the Boundary: The Science and Art of Western Map Making, As Exemplified by William H. Emory and his Colleagues of the U.S. Corps of Topographical Engineers," a paper presented at the Sesquicentennial Mexican War Symposium, October 2-3, 1997, Fort Gibson, Oklahoma, under the auspices of the Oklahoma State Historical Society. These papers are available on-line at, respectively, <http://calcite.rocky.edu/octa/harland.htm> and <http://ourworld.compuserve.com/homepages/pderickson/Finding.htm>.

SIMON NEWCOMB AT THE NAUTICAL ALMANAC OFFICE

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If we judge a scientist's influence by recognition from his contemporaries, then Simon Newcomb stands out as the most influential American scientist of the late nineteenth century. The American and international scientific communities repeatedly honored this mathematical astronomer for his comprehensive studies of the motions and positions of the sun, moon, planets, and stars and his supportive studies in mathematics and physics. Conducted primarily during the decades following the Civil War, these investigations culminated in definitive sets of astronomical constants, tables, and computational methods. Significantly, he carried out these investigations at the United States Naval Observatory and, particularly, the Nautical Almanac Office.

Despite his contemporary renown, Newcomb slipped from prominence following his death in 1909. Apparently, the contributions of this "last of the great masters" of classical, Newtonian astronomy—to use Albert Einstein's epithet—were overshadowed by the new astronomy of spectroscopic observations and relativistic theories.¹ Though Newcomb lifted classical astronomy to a new level of refinement, few non-astronomers could appreciate the significance of his precise measurements and complex calculations; and unfortunately, he lacked that single major discovery or breakthrough to which non-astronomers could readily attach his name.

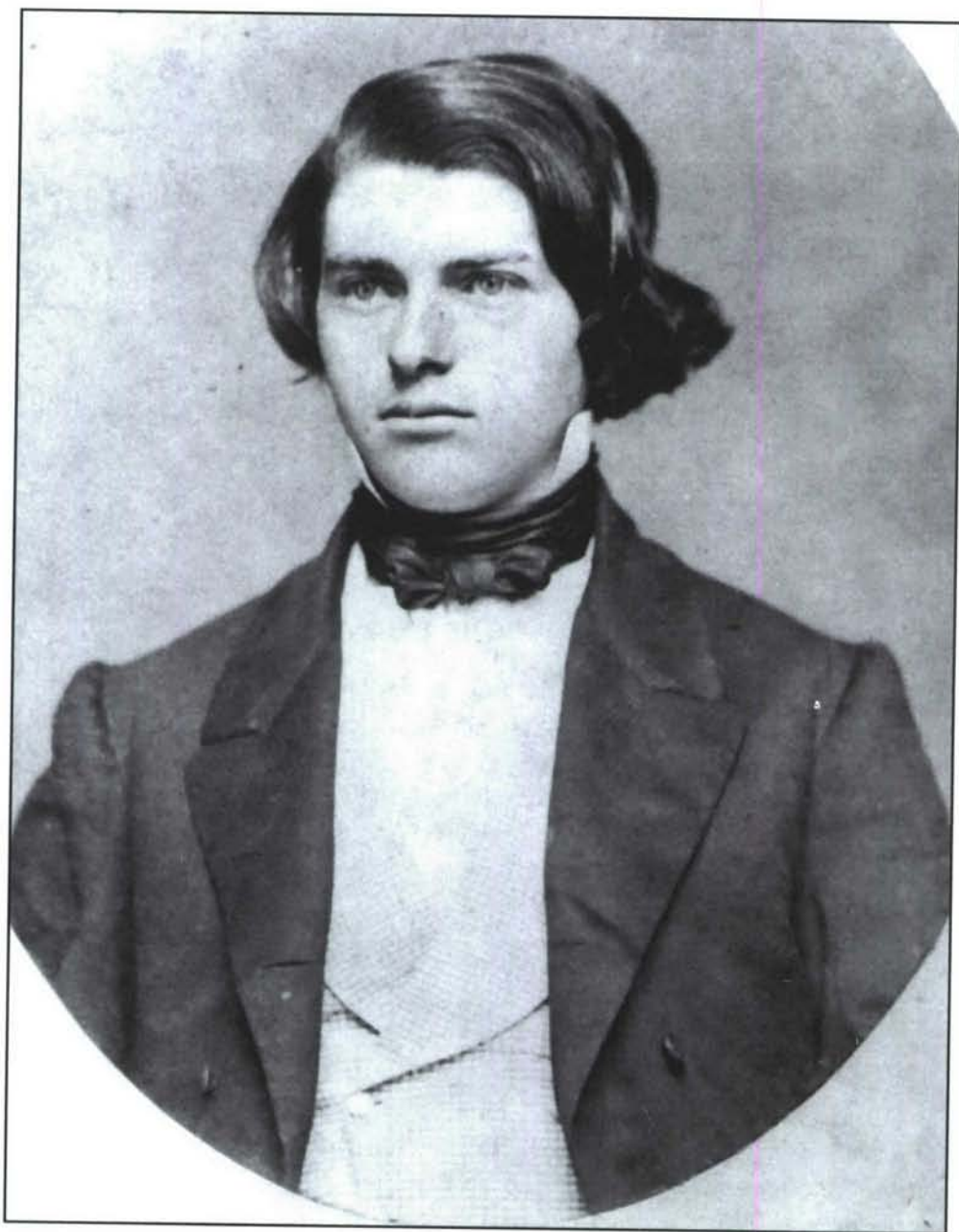
On the occasion of the sesquicentennial of the Nautical Almanac Office, it is appropriate to remind ourselves of the accomplishments of this once celebrated astronomer. More particularly, it is appropriate to remind ourselves of the degree to which his distinguished career intertwined with the early history of the Almanac Office.

Computer

Newcomb was born in 1835 in Nova Scotia, the son of an itinerant school teacher. Through reading and home instruction, he gained a solid,

basic education. At age sixteen, showing much intellectual promise, he became an apprentice to a New Brunswick herbal "doctor." After two years with the herbalist, however, he grew disillusioned and broke the agreement by fleeing to the United States. In 1854, the young immigrant began a series of jobs as a teacher and tutor in rural Maryland. All the while, he continued to read and write, following interests in especially mathematical astronomy. Living not too far from the Smithsonian Institution in Washington, he drew on its library and began to interact with its director, prominent physical scientist Joseph Henry. In late 1856, one of Henry's scientific contacts arranged for the bright, twenty-one-year-old tutor to assume the position of "computer" under the direction of astronomer Joseph Winlock at the Nautical Almanac Office in Cambridge, Massachusetts.² Congress had established this government agency, under the control of the Secretary of the Navy, seven years earlier. Becoming a computer meant joining a small band that performed the routine mathematical calculations for various lunar and planetary tables useful in navigation and astronomy—tables published in the *American Ephemeris*. Newcomb traveled to Cambridge in late December, 1856, and soon began his new work: "I date the fruition of my hopes, my actual citizenship of the world of my childish dreams and youthful aspirations, from one frosty morning in January, 1857, when I took my seat before a blazing fire in the 'Nautical Almanac' office. . . ." Indeed, Newcomb had chanced onto the nation's leading scientific metropolis, Boston-Cambridge, the nation's largest telescope, the fifteen-inch refractor at the Harvard observatory, and the nation's leading mathematical astronomer, Benjamin Peirce.³

Newcomb quickly distinguished himself at the Almanac Office. Within half-a-year, according to a report submitted by superintendent Winlock, the young computer showed "evidence of Mathematical talent and knowledge very unusual for his age and limited opportunities. . . . With his love for mathematics and his industry, he will in a short time be one of the most suitable assistants engaged in our work."⁴ Happily, like his fellow computers who performed the methodical calculations for the astronomical tables, Newcomb had much free time in his daily schedule of work. He allocated some of the hours to his favorite pastime, chess. (In a diary entry written after the office was visited by two eminent Harvard scientists, Newcomb sheepishly revealed: "Profs Peirce and Agassiz came into the office while I was playing chess with Edmunds." Eight months later, Newcomb recorded that the lax work schedule was being tightened slightly: "An order issued in the N. Alm. Office that the computers should



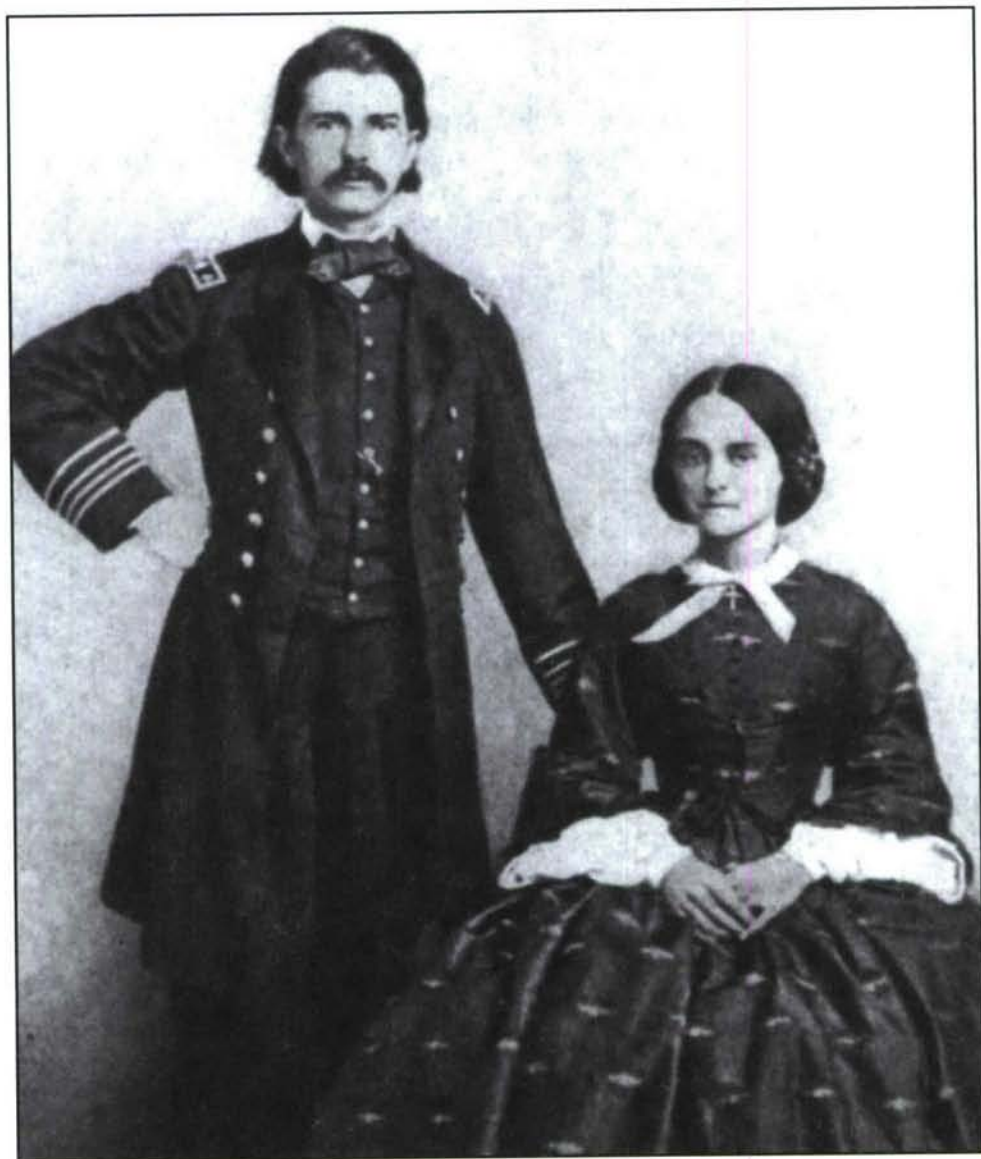
Simon Newcomb in 1857 at age twenty-two, while a student at Harvard's Lawrence Scientific School, and a computer at the Nautical Almanac Office in Cambridge. (Photo courtesy of the Manuscript Division, Library of Congress.)

hereafter work six hours per day.”⁵) He also found amusement in philosophical discussions with his co-workers, especially Chauncey Wright.⁶ In addition, he had enough open hours to enroll as a student of mathematics at Harvard’s Lawrence Scientific School. Studying primarily under Benjamin Peirce, Newcomb was in a loosely structured program that required little formal course work.⁷

Benjamin Peirce was, as Newcomb stated, “the leading mathematician of America.” He had published complex theoretical studies of the positions and motions of the planets, moon, and comets, including mathematical analyses of errors of observation. Besides being a professor at the Scientific School, he served as theoretical advisor for the Almanac Office. Under Peirce’s deft tutelage, Newcomb graduated two years later, *summa cum laude*, with a bachelor of science degree.⁸

Remaining in Cambridge, Newcomb soon demonstrated that his skills in mathematical astronomy were developing well beyond the requirements for an assistant at the Almanac Office. Building on studies that he began in 1858, he crafted a precise analysis of the orbital motions of the asteroids, the small bodies orbiting between Mars and Jupiter. He demonstrated that the asteroids could not have originated, as was commonly believed, from the shattering of a single planet. Though he published his main results in 1860 in the *Memoirs* of the American Academy of Arts and Sciences, he rehashed the findings two years later in the German journal *Astronomische Nachrichten*. He later remarked that the asteroid study was the first of his research projects “to attract especial notice in foreign scientific journals.”⁹

In 1861, a fellow Cambridge astronomer, Benjamin Gould, alerted Newcomb to an opening for a “Professor of Mathematics” at the United States Naval Observatory in Washington. Founded three decades earlier ostensibly to meet the Navy’s navigational needs, this agency had evolved into a major research observatory; the Navy relied on a commissioned corps of “professors” to provide technical expertise and instruction at the Observatory as well as at the U. S. Naval Academy. “I think,” Gould wrote, “that an active effort on the part of your friends would secure the place for you.” Listing as references such influential “friends” as Peirce, Henry, and Gould, Newcomb obtained the position. Thus, with a letter of appointment from President Abraham Lincoln, he actually began his post-Cambridge career as an observational astronomer. He would spend the remainder of the 1860s mainly performing basic observations of stars,



Simon Newcomb married Mary Hassler, the granddaughter of Ferdinand Hassler, eminent geodesist and founder of the U.S. Coast Survey. The couple--pictured shortly after their marriage in 1863, with Simon in full Navy regalia--went on to have three daughters, Anita, Emily, and Anna. The oldest, Anita Newcomb McGee, became a prominent physician and founder of the Army Nurse Corps. (Photo reproduced from *McClure's Magazine*, Oct. 1910.)

pinpointing their right ascensions (celestial longitudes) using a transit instrument and their declinations (celestial latitudes) using a mural circle.

Indeed, though he came to Washington inexperienced in observational work, he would soon take the lead in organizing and unifying the Naval Observatory's methods and then, using a new transit instrument, take on the challenge of disclosing systematic errors in star's right ascensions that plagued leading observatories around the world. To his satisfaction, Newcomb once again found himself in a lax work regimen. He recalled that whenever he or his fellow observers tired of their late-night vigils, "we could 'vote it cloudy' and go out for a plate of oysters at a neighboring restaurant." He also recalled that the young astronomy "professors" found it pleasant "to wear the brilliant uniform of their rank, enjoy the protection of the Navy Department, and be looked upon, one and all, as able official astronomers." "As things go in Washington," he added in a similar vein, "the man who does his work in a fine public building can gain consideration for it much more readily than if he does it in a hired office. . . ." Incidentally, in 1858 while still in Massachusetts, Newcomb had begun the procedure to become a citizen of the United States and became naturalized six years later in the District of Columbia.¹⁰

Professor

Though he spent his first years in Washington principally making exact determinations of stellar positions, Newcomb took advantage of the free time at the Naval Observatory to reassert his interest in mathematical astronomy. As the decade of the 1860s unfolded, he returned to theoretical studies of especially the planets and the moon. Following in the footsteps of Peirce and other mentors, he felt challenged to formulate abstract mathematical expressions to account for actual planetary and lunar observations. This involved making complex calculations of orbital deviations caused by the gravitational perturbations of interacting celestial bodies, and then constructing positional tables that would allow comparisons with observational data. Seeking a new degree of analytic percision, Newcomb tackled a particularly attractive pair of planets, Uranus and its recently discovered companion, Neptune (observed in 1846 following the predictions of Urbain J. J. Leverrier and John Adams). By 1868, he had completed provisional studies of the two planets and was ready to begin a five year investigation that culminated in definitive tables

for Uranus—tables that included the perturbational effects of especially Neptune.¹¹

Professor Newcomb also found time at the Naval Observatory to hone the mathematical theory of the moon's motion. Drawing Newcomb to the lunar problem were not only recent theories by Peter Hansen and Charles Delaunay but also the intrinsic complexity of the moon's orbit. Newcomb would later come to view his lunar research as the centerpiece of his life's work in mathematical astronomy. In particular, by 1869, having completed his reappraisal of star positions, he decided to pick up the strands of some of his earlier lunar investigations by initiating a concerted study of the moon's motion. Concerned, however, that his post in an observational facility precluded him from engaging in this intensive theoretical study—and seeking, more generally, to advance his career—he petitioned for a transfer to the more mathematically inclined Nautical Almanac Office. Though he gained the support of Peirce and Henry, his superiors judged the move unnecessary; they agreed, nevertheless, that Newcomb could proceed with the research under the auspices of the Naval Observatory. In the next few years, he published a series of innovative lunar studies in French, German, and British journals.

What he considered his biggest lunar coup came, however, in 1871 as part of a memorable first trip to Europe. In France, he resurrected old records at the Paris Observatory and ferreted out lunar positional data extending back to 1675. This six weeks of archival digging (made in the thick of the civil hostilities surrounding the Paris Commune), followed by three or four years of calculation and analysis, added seventy-five years of data to the lunar record, dramatically demonstrating the deficiency of accepted lunar tables.

Newcomb's colleagues at home and abroad were increasingly impressed by his innovations in mathematical astronomy. In 1874, in Britain, the Royal Astronomical Society presented its gold medal to the thirty-nine-year-old American. In the formal citation read at the award ceremony, president Arthur Cayley proclaimed that all of Newcomb's astronomical writings exhibit "a combination, on the one hand, of mathematical skill and power and on the other hand of good hard work." "The Memoir on the Lunar Theory," he continued, "contains the successful development of a highly original idea, and cannot but be regarded as a great step in advance in the method of the variation of the elements and in theoretical dynamics generally; the two sets of planetary tables [for Neptune and Uranus] are works of immense labour, embodying

results only attainable by the exercise of such labour under the guidance of profound mathematical skill—and which are needs in the present state of Astronomy.” Cayley added, “we have done well in the award of our medal.”¹²

To be sure, even before winning the medal for studies of particularly the moon, Neptune, and Uranus, Newcomb was gaining professional recognition, as evidenced by invitations to become a member of elite national and international scientific organizations. But the British gold medal signalled the beginning of a cascade of honors that would persist for the remainder of his career. Merely four years after the British award, for example, the Dutch Academy of Science presented him with the Huyghens gold medal. Awarded only every other year, this prestigious medal rotated in twenty-year cycles between the different natural sciences, with the award of 1878 going to the one astronomer who over the prior two decades “distinguished himself in an exceptional manner.”¹³

Newcomb completed his tenure at the Naval Observatory with two major observational projects. In 1873, his superiors placed him in charge of a new telescope—not just any telescope, but the nation’s largest operating refractor. Having helped initiate and guide the effort to obtain this massive telescope, with its twenty-six inch aperture and thirty-five foot tube, he found himself awe-struck when he became the first astronomer to test the instrument: “I was filled with the consciousness that I was looking at the stars through the most powerful telescope that had ever been pointed at the heavens, and wondered what mysteries might be unfolded.” The mystery that he first tried to solve involved a possible second satellite of Neptune; though unsuccessful in his search, he did collect orbital data on the known moons of Neptune and Uranus to use in calculating more exact values of the planets’ masses, critical constants in the construction of the planetary tables.¹⁴ He also took the lead in a second major project: mounting an American expedition, composed of eight separate parties, to track the 1874 transit of Venus. While Newcomb remained in Washington helping coordinate the project, the American parties joined European astronomers, all stationed at different sites in the eastern hemisphere, in applying triangulation techniques to the passage of Venus over the solar disk to better fix the earth-sun distance. Though Newcomb introduced innovative photographic apparatus, “unpropitious” weather largely frustrated the efforts of the American and European parties. This disappointing experience would prompt Newcomb to argue

against new expeditions for the coming transit of 1882, though it would be the last until 2004. He felt that the sun's distance could be better determined using calculations involving the velocity of light and the earth's orbital velocity (that is, involving what is technically known as the aberration of light). Whereas he went on to exploit the latter method, he deferred to his colleagues' preferences, consenting to lead an 1882 expedition to the Cape of Good Hope. While the new international transit data enabled him to refine the earth-sun distance for personal use in his planetary tables, he lamented that the American results were never published.

Although Newcomb left no published record of the Cape of Good Hope transit expedition, he did leave another type of tangible artifact that he hoped would be of use to his astronomical descendants 122 years later--in 2004, on the occasion of the next Venus transit. At the observation station, he left securely anchored in the ground a set of iron pillars that had held the expedition's apparatus for photographing the sun. "Whether they will remain there until the transit of 2004," Newcomb mused, "I do not know, but cannot help entertaining a sentimental wish that, when the time of that transit arrives, the phenomenon will be observed from the same station, and the pillars be found in such a condition that they can again be used." He left instructions for finding the site: in the town of Wellington, forty miles northeast of Cape Town, on the grounds of an American style "young ladies' school" run by a New England school mistress named Ferguson.¹⁵

Superintendent

After serving at the Naval Observatory since 1861 and after much political maneuvering, Newcomb gained appointment in 1877 as superintendent of the Navy's Nautical Almanac Office. The office was now located in Washington, having been moved from Cambridge in 1866. He believed, as he stated later in his *Reminiscences*, that as head of this Washington agency dealing with applied and basic astronomy, he was "in a position of recognized responsibility" where he "could make plans with assurance of being able to carry them out. . . ." In addition, he felt that as a top scientist in government he could help remedy what he perceived in the United States to be "an absence of touch between the scientific and literary classes on one side, and 'politics' on the other." His appraisal of the scientific opportunities at the Almanac Office, an agency that he aggressively restructured, would prove to be reasonably accurate. His



Newcomb in the 1870s. He eventually achieved the “relative” rank of rear admiral in the U.S. Navy. At his death in 1909, he was buried with full military honors in Arlington National Cemetery. (Photo courtesy of the Smithsonian Institution Archives.)

appraisal, however, of the opportunities in government service to improve communication between scientists and politicians would prove to be overly optimistic. After retiring from the Almanac Office in 1897, at the mandatory Naval retirement age of sixty-two, he would still be lamenting the “want of touch between our academic and political classes.” Somewhat disillusioned, he would even come to question the sagacity of his decision to remain a government scientist.¹⁶

Newcomb proved a capable administrator after taking charge of the Nautical Almanac Office. “Practically I had complete control of the work of the office,” he recalled, “and was thus, metaphorically speaking, able to work with untied hands.” Freedom to set the research agenda was important to Newcomb: While still at the Naval Observatory, he had chafed under the leadership of those Naval administrators whom he perceived to lack scientific sensitivity. (Over the next twenty-five years, he would work behind the scenes in support of civilian astronomers’ attempts—ultimately unsuccessful—to wrest control of the Naval Observatory.¹⁷) He soon reinvigorated the Almanac Office, securing new quarters in a recently completed government building and assembling a staff of eight or ten mathematical assistants, including the talented George W. Hill. Impressed by the success of Sir George Airy, the Astronomer Royal, in systemizing activities at Greenwich—and, to a lesser extent, Leverrier in organizing the Paris Observatory—Newcomb adopted a managerial approach characterized by efficiency and economy. He insisted, for example, that promotion be based on merit rather than seniority and that salary be commensurate with time spent on a job. “These economies went on increasing year by year,” he explained, “and every dollar that was saved went into the work of making the tables necessary for the future use of the Ephemeris.” The Navy also contributed to the economies by, in 1893, relocating the Nautical Almanac Office to the Naval Observatory’s new facility a few miles northwest of downtown Washington.¹⁸

While he always carefully justified the office’s work in terms of its indispensability to American ships navigating the world’s oceans, Newcomb was personally and primarily interested in the basic science behind the navigational tables. In this scientific realm, he also proved to be a capable administrator, charting a systematic and exhaustive course of research.

The programme of work which I mapped out, involved, as one branch of it, a discussion of all the observations of value on the positions of the sun, moon, and planets, and incidentally, on the bright fixed stars, made at the leading observatories of the world since 1750. One might almost say it involved repeating, in a space of ten or fifteen years, an important part of the world's work in astronomy for more than a century past. Of course, this was impossible to carry out in all its completeness. In most cases what I was obliged practically to confine myself to was a correction of the reductions already made and published. Still, the job was one with which I do not think any astronomical one ever before attempted by a single person could compare in extent. . . . The other branches of the work were . . . the computation of the formulae for the perturbation of the various planets by each other.

To ease publication of findings, Newcomb launched in the early 1880s the *Astronomical Papers Prepared for the Use of the American Ephemeris and Nautical Almanac*. This complemented the office's mandated issuance of the *American Ephemeris and Nautical Almanac*.

By 1894, seventeen years after taking over the Almanac Office and thirty-three years since joining the Naval Observatory, he had completed the bulk of the research program. Except for the final step of constructing tables for the planets beyond Mars and a few other loose ends involving especially the moon's orbit, he had largely succeeded in bringing to a close the reduction of the observations and the determination of the planetary orbits. One colleague later described the effort as being "of herculean and monumental proportions." Twentieth-century commentators would look back, for example, at his analysis of Mercury's orbit, noticing that he had pinpointed the modern value of a slight orbital anomaly (known as precession of the perihelion and first detected by Leverrier). This anomaly, which Newcomb suspected defied conventional Newtonian gravitational explanations, would become intelligible only through Albert Einstein's general theory of relativity. Indeed, Einstein would describe Newcomb's lifework as being "of monumental importance to astronomy."¹⁹ But Newcomb's "preliminary results," which he published early in 1895 as *The Elements of the Four Inner Planets and the Fundamental Constants of Astronomy*, also generated a more immediate

response. The results helped actuate an international movement to set the world's astronomical ephemerides on a more homogeneous basis—a collaborative readjustment that Newcomb had been urging for a long time and that finally gained momentum during his retirement years.

Retiree

Retirement meant for Newcomb a realignment of work, not an end or even slackening of research, writing, and public speaking. Forced by law to leave Naval employ at age sixty-two, he stepped down from the superintendency of the Nautical Almanac Office on his birthday in March of 1897. A special, albeit modest congressional appropriation and then, beginning in 1903, generous grants from the new Carnegie Institution in Washington enabled the distinguished retiree to maintain his intense schedule of research and professional interaction. He assumed the lead in the major international project to bring order to astronomical computations through the adoption of uniform constants and consistent data. Indeed, as historian Arthur Norberg has shown, Newcomb did his job so well that many of his numerical values would remain in official use until the mid-century arrival of electronic computers and artificial satellites. Also during retirement, Newcomb persisted with his long-standing work on planetary tables, especially the motion of the moon. Furthermore, continuing to display great drive, he helped organize and, in 1899, became the first president of the Astronomical and Astrophysical Society of America (later renamed the American Astronomical Society).²⁰

All the while, top awards and honors were coming to him at an increasing rate from around the nation and world. In fact, his formal government career ended propitiously, coinciding with him being named in 1895 one of eight Foreign Associates of the Paris Academy of Sciences. Writing anonymously in the *Nation*, Charles Peirce explained the salience of this designation. "This is universally acknowledged to be the greatest public honor that can be conferred upon a non-French man of science. Newcomb is the first citizen of the United States to receive it (if we are right in thinking that Louis Agassiz never completed his citizenship). It has never yet been bestowed upon a native citizen of the United States, although Franklin and Rumford received it." (Peirce, of course, overlooked that Newcomb was not a native, but a naturalized citizen who had been born in Nova Scotia.) A year after retiring from the Almanac Office, Newcomb also became the first recipient of the Bruce Medal, endowed by Catherine Wolfe Bruce of New York City and awarded by the

Astronomical Society of the Pacific. In describing the international process used to select the most deserving astronomer from among many brilliant candidates, Society president William Alvord reported that "one name stood forward so prominently in the communications from heads of six leading observatories of the world, that the Directors of this Society could but set the seal of their approval upon the verdict of his peers, and award the first Bruce Medal to Professor Simon Newcomb."²¹

In that Simon Newcomb's accomplishments were intertwined with the federal scientific agencies that sustained his researches, his awards and honors also endure as tributes to the U.S. Naval Observatory and, particularly, the Nautical Almanac Office.

NOTES

This sesquicentennial paper is drawn from, with minor additions and revisions, the author's Newcomb biography, used with permission of University of California Press. For fuller coverage and documentation, please refer to Albert E. Moyer, *A Scientist's Voice in American Culture: Simon Newcomb and the Rhetoric of Scientific Method* (Los Angeles: University of California Press, 1992), particularly the preface and chapters 2, 3, 5, and 11.

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4. Winlock to Capt. D. N. Ingraham, Naval Observatory Records, National Archives and Records Service, quoted in Norberg, "Newcomb's Early Astronomical Career," 214.

5. Newcomb, Diary for 1858, 2 Feb. 1858, 27 Sept. 1858, SNP, Box 1.

6. See, e.g., Diary for 1859, 14 April 1859, SNP, Box 1.

7. *Catalogue of the Officers and Students of Harvard University for the Academical Year 1856-57, Second Term* (Cambridge, Mass.: John Bartlett, 1857), 67, 69-73. Newcomb, "Formative Influences," 189-90; Newcomb, *Reminiscences*, 74-75.

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18. For Newcomb's later decades see Newcomb, *Reminiscences*, 215-233; Campbell, "Simon Newcomb," 8-18.
19. Campbell, "Simon Newcomb," 10. Brasch, "Einstein's Appreciation of Simon Newcomb," 248-49. Abraham Pais, *'Subtle is the Lord . . .': The Science and the Life of Albert Einstein* (Oxford: Oxford University Press, 1982), 253-54. For Jean Chazy's critique in the 1920s of Newcomb's work on the advance of the perihelion of Mercury, see Pierre Costable, "Jean Cheazy," *Dictionary of Scientific Biography*.
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WALLACE ECKERT, COMPUTERS, AND THE NAUTICAL ALMANAC OFFICE

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Introduction

It is a great privilege for me to be invited to this 150th anniversary symposium of the Nautical Almanac Office, and to have the opportunity to speak about Wallace J. Eckert. I have tremendous respect for his work and personality, but I have to warn you that I am neither a professional astronomer nor a historian. I met Eckert only in 1963 when I joined the IBM Watson Laboratory at Columbia University of which he had been the founder and at the time still the director. As a research physicist I never worked with him, but I saw him regularly and had a chance to talk about his work, and to listen to many stories. Although we went separately, both of us discussed and then viewed the great solar eclipse of March 7, 1970 from Virginia Beach.

Eckert retired in 1967, but he continued to come to the laboratory in order to supervise the work on lunar theory that was carried out by a programmer, Sarah Bellesheim. The laboratory was closed in 1970, and everybody was moved to IBM's main research center in Yorktown Heights. Eckert became ill shortly thereafter, and so I was asked to keep an eye on the work in lunar theory. I had gotten interested in classical mechanics meanwhile, and I enjoyed learning about celestial mechanics. But Eckert died in 1971, and never saw the complete result. I was fortunate to team up with Dieter Schmidt, in order to bring the whole project to its conclusion, and get Eckert's great work published as planned in the *Astronomical Papers of the American Ephemeris and Nautical Almanac*.

Before I get started with my story, let me acknowledge a helpful visit with Dorrit Hoffleit at the Astronomy Department of Yale University.

An Auspicious Start

Wallace Eckert was born in 1902, and raised on a farm in Pennsylvania. He received a bachelor's degree from Oberlin College in 1925, and a master's degree from Amherst College in 1926. Then he went

to Yale to work on a Ph.D. in astronomy. Ernest W. Brown sparked his life-long interest in numerical processing in astronomy as well as in the foundations of lunar theory. At the same time, Eckert was also involved in Columbia University's astronomy department as a graduate assistant, and then he joined the faculty as assistant professor after getting his Ph.D. from Yale University.¹ He reminisced later:

When I started in 1926 as an assistant at Columbia, the logarithm was just being put to bed and the desk calculator was beginning to take over computation work. It was an exciting time as we began to see the real possibilities of automatic computation emerging.

In these years around 1930, Eckert got the most important inspiration for his life's work, and I think that they came from three sources:

i) Ernest William Brown (1866-1938), born and educated in England, who came first to Haverford College in 1891 and then to Yale in 1907, largely because he was promised support for his great lunar project;

ii) Leslie John Comrie (1893-1950), a New Zealander who had been wounded on the Western front in WWI, and then stayed on in England where he eventually became superintendent of the Nautical Almanac Office;

iii) Benjamin D. Wood, a Texan who came to Columbia University in 1921 as an instructor, and started various programs in the statistical aspects of education. In the fall of 1928, he talked Thomas J. Watson, Sr., president of IBM, into providing three truckloads of IBM equipment to start the Columbia Statistical Bureau.

Comrie reported 1932 in the *Monthly Notices of the Royal Astronomical Society*² about his innovations at His Majesty's Nautical Almanac Office. A few quotes from these two papers give a good impression of the situation from which Eckert started in his own work, and also of the progress that he was still to realize in the ensuing 20 years.

During the past six years the calculations done in HM Nautical Almanac Office have been completely mechanized. Not a single logarithm is now used. The older generation has been succeeded by one which knows only how to produce figures mechanically. The policy of the Office is not to design special machines, but rather to adapt existing commercial machines to its requirements.

Although logarithms were gone, multiplications still had to be carried out by repeated addition and appropriate shifts. But there were already efforts to integrate directly some differential equations.

Three years ago a Burroughs Class 11 machine was installed to perform what might be called mechanical integration - here the building up of a function from its known finite second differences. In other words, the machine is really a difference engine, realising the ambitions of Charles Babbage, to whom, it may be recalled, the first Gold Medal of our Society was awarded in 1823 for "his invention of an engine for calculating mathematical and astronomical tables".

It may be recalled that E W Brown spent some twenty years to produce the ultimate tables for the calculation of the Moon's motion. His Tables of the Moon were published in 1919, and were generally adopted by all the national ephemerides as the basis for their almanacs. Comrie made a determined effort to use these tables more efficiently.³

Although well arranged, the work using them is laborious, and, before the advent of the Hollerith machine, represented the continuous work of two skilled computers. The mechanical methods that have been applied to certain portions of the work have eliminated much fatigue, increased tenfold the speed with which results can be obtained, and the cost to one-quarter of its former amount.

But in spite of this very useful application of the existing machines, Comrie does not seem to envisage the eventual replacement of the tables by a more direct process, either based on the underlying trigonometric series or on direct integration of the equations of motion.

A Hollerith installation was used in HM Nautical Almanac Office for seven months in 1929; actually punching was started six months before arrival of the sorter and tabulator, as it was necessary to punch 20,000,000 holes in half a million cards. The work described on long- and short-period nutation, and on double entry tables, as well as that of most of the single-entry tables, was

carried out to the year 2000. The greater part of the cost was incurred in doing the first ten years, which would have sufficed for immediate needs. But to continue for the next 55 years with a trained and organized staff added very little to the cost, and was certainly more economical than the re-training and re-organizing ten years later. Moreover, there is little likelihood of Brown's Tables being superseded before the end of the century; any acquisition of knowledge of the Moon during the next seven decades is almost certain to be expressed in the form of corrections to Brown's Tables, not in the form of new tables.

Eckert was only 9 years younger than Comrie, but I have never come across any prediction he made that limited the long-range future of celestial mechanics in this short-sighted manner. In his own sweet way Eckert consistently pushed for the most advanced technology, even if waiting a few years could have succeeded in lessening some more of the drudgery.

Columbia's Astronomical Computing Bureau

For his first few years at Columbia, Eckert used the facilities of the Columbia Statistical Bureau that Benjamin Wood had organized with the help of IBM's donated equipment. But in 1933 he asked Wood to approach T.J. Watson, Sr. with a substantial shopping list. Some of the items required modifications to make them suitable for scientific operations, such as IBM's new model 601 Multiplying Punch. This equipment found a home in a special room of Columbia's Astronomy Department, and was organized as the Thomas J Watson Astronomical Computing Bureau with Eckert as the director.⁴ Ernest W Brown was on the Board, along with T H Brown of Harvard, Henry N Russell of Princeton, and CH Tomkinson representing IBM. In return T J Watson became a trustee of Columbia University, whose president then became a member of IBM's Board of Directors. It was the beginning of a continuing sweetheart deal between the corporation and the university that was greatly expanded after WWII, but then quietly dissolved in 1970 after the student rebellion in 1968.

Eckert now worked closely with the engineers, and he was probably the first to develop a so-called mechanical programmer. This is a box of pluggable relays with some twenty settings of switches so that he could coordinate the functions of his tabulating machines. Similar ideas,

sometimes on a bigger scale, were tried out at half-a-dozen places in the US and in Germany, but only at the end of the 1930's and the beginnings of the 1940's.

Relatively few articles are left in the scientific literature to describe these pioneering efforts in more than general terms. There is, however, one slender volume ⁵ entitled "Punched Card Methods in Scientific Computation" by W. J. Eckert, published by The Thomas J. Watson Astronomical Computing Laboratory, Columbia University, January 1940. It became the source of information for engineers and scientists who got involved in constructing and using machines for computer-like applications. Some of the better-known builders of the early computers, like Vannevar Bush at MIT, J. Presper Eckert of the ENIAC, and Howard Aiken at Harvard, got their first introduction in the famous orange book.

The various machines from the IBM store are described with their function and capabilities. Then follow discussions of some special tasks like the construction of special tables, interpolation and mechanical quadrature, harmonic analysis and synthesis, the multiplication of large series, and the numerical solution of differential equations. The last part treats astronomical applications: construction of a star catalog from photographic plates, stellar photometry, numerical lunar theory, and planetary perturbations. Finally, there is a list of card catalogues and tables that are available at the Astronomical Bureau for outside users.

The Air Almanac

On the basis of this marvelous work Eckert was promoted to full professor at Columbia University in 1940. But in the fall of 1939 he had been asked to become the Director of the Nautical Almanac Office at the US Naval Observatory in Washington DC, and he started the job in early 1940. He recalls: ⁶ "They had no automatic equipment. Every digit was written by hand and read and written repeatedly They didn't have a machine that would print figures automatically. They had desk calculators."

Eckert was then 37 years old, and he stayed for a little over four years. It was clearly the most important period of his life. He felt that he had done his most valuable work at the Nautical Almanac Office, and the most important achievement there was obviously the Air Almanac. Eckert wrote an article ⁷ for *Sky and Telescope* on air almanacs which appeared in the November issue of 1944. It is somewhat terse, but it gives a rather complete history. The first air almanac was American, and published in

Washington for 1933. It was soon imitated by the Germans, the French, and the British, in that order; they are all of the same design, and rather voluminous with 730 ($= 2 \times 365$) pages per year plus a few appendices.

Basically, the Greenwich Hour Angle and the Declination is recorded for Sun, Venus, Mars, Jupiter, and Moon every 10 minutes of each day, in degrees with an accuracy of 1 minute of arc. Of course there is additional information on certain fixed stars, on risings and settings of Sun and Moon for various latitudes, the age of the Moon, the first point of Aries, and so on. Eckert's great merit, as well as his pride and joy for the rest of his life, was that the intervention of human hands was almost completely eliminated in the production and printing of this data. No error has ever been reported.⁸ After describing the steps in this process, he announces: "The efficacy and accuracy of this method are revolutionary."

The first Air Almanac from Eckert's shop came out just in time for use by the American armed forces in World War II. Although it is difficult to quantify its advantages, Eckert estimates that there were about 50,000 users, and there is general agreement that it was a vital navigational aid for the planes of the US Army and Navy; the Air Force came into being as an independent branch of the Armed Forces only after the war.

Perhaps less well-known is the effect of Eckert's pioneering work in the 1930's on other urgent enterprises that started in 1940.⁹ The Aberdeen Proving Ground of the US Army, the Los Alamos Scientific Laboratory of the Manhattan Project, and other laboratories of strategic importance had their computing activities patterned after those at Columbia University and the Naval Observatory. Needless to say that IBM was eager to provide the machinery.

The IBM Watson (Scientific Computing) Laboratory

It does not come as a surprise that the IBM corporation did not even wait for the end of WWII before it started to hire people to bring science into the design of its machines. Eckert became the first Ph.D. to be hired, and at the same time he took up his professorship in Celestial Mechanics at Columbia University. He got his own building, first a renovated former fraternity house on 116-th Street, and then a former women's residence for students at the Julliard School of Music on 115-th Street. It was now called the Watson Scientific Computing Laboratory, and became the hub of many activities, including many people from other company locations, from government, universities, and other industries.

It was a time when individuals with ideas, initiative, and energy were able to pursue different projects without the burden of a large staff and long-term planning. In Eckert's words: ¹⁰

The interaction was very close This was a very informal place. We felt that the people who were coming to solve problems should mix with the people who were learning and were giving courses. We had always problems of our own, of course, that we were interested in getting solved. So the place was more like a university laboratory than a computing center. People sat around and discussed their problems and they would wait for the machines, and while one person was using one machine, somebody else was using another. So it was a very intimate arrangement.

A number of computers were designed and built under Eckert's general supervision, ¹¹ monsters by our present-day standards, but the first and best of their kind at the time. The Selective Sequence Electronic Calculator (SSEC) of 1947 used 13,000 vacuum tubes together with 21,000 electromagnetic relays. It was a capricious contraption, and the last bugs had to be ironed out while the honored guests at IBM's headquarters on 590 Madison Avenue were served a sumptuous luncheon. But according to one of the participants, in the dedication ceremonies that followed, the SSEC performed flawlessly, grinding out several dozen good positions of the Moon.

Actually, the SSEC was used to produce Eckert's Improved Lunar Ephemeris (ILE); ¹² also, in collaboration with Dirk Brouwer of Yale University and Gerald Clemence of the US Naval Observatory, the Coordinates of the Five Outer Planets 1653-2060 were computed on the SSEC. ¹³ An engineer, John Lentz, perfected the Star Measuring and Recording Machine, which was then used extensively by Rebecca Jones to work on Yale's Star Catalog and Yale's Minor Planet Project. ¹⁴

The experience with the SSEC led IBM into building various upgrades that became commercially available in the early 1950's. The unexpectedly successful IBM 650 was superseded by the 701 Defense Calculator and its descendants. But Eckert got involved in another computer giant, the Naval Ordnance Research Calculator (NORC) which was put into service in 1954. The picture of the official ceremony ¹⁵ shows Eckert in front of one of the big instrument panels with the Watson family (father, mother, and son) on his right and two Rear Admirals plus

one Captain on his left, not bad for a boy from a dairy farm in Pennsylvania!

Before I get, finally, to Eckert's scientific work, let me shortly discuss another slender volume ¹⁶ that he wrote with Rebecca Jones under the title "Faster, Faster; A Simple Description of a Giant Electronic Calculator and the Problems it Solves", McGraw-Hill 1955. It describes the NORC in some detail, not so much the physical machinery as its logical procedures. It was made from resistors, crystal rectifiers, capacitors, vacuum tubes, inductors, pulse transformers, a total of 200,000 components, and was able to multiply two ten-digit numbers in a millisecond, an estimated improvement by a factor 100,000 compared to a key-controlled mechanical desk calculator. If one allows for the time from 1925 to 1955, the technical advance has been rather more slow in recent decades!

Still, the physical size and clumsiness is mind-boggling by present-day standards. The basic pulse rate was 1 microsecond; the "memory", or random-access storage, could accept or recall a "word" of 66 bits in 8 microseconds from any one of its 3600 locations. These were found in 66 "drawers" each of which contained 4 storage tubes, i.e., ordinary TV monitors on whose faces the bits were inscribed. There were also 8 magnetic tape units that could read fast but not randomly, at the rate of 70,000 characters a second. Basic input of the NORC was through reading of punched cards at a rate of 450 per minute, and the output in the form of print was 19 words per minute. The handling of these facilities is described in "Faster, Faster", including some of the basic arithmetical operations.

The last chapter "What is there to calculate?" was written by Llewellyn H. Thomas, a well-known all-round genius in physics, as well as a close friend and collaborator of Eckert. Thomas had stunned the world early in his career by deriving the effect of Einstein's relativity on the Moon, and then applying the same method to the spin-orbit coupling of the electron in an atom. He was also the inventor of a simple method to calculate the charge density in atoms, molecules, and metals. Now he discussed how to treat problems in external ballistics, the astronomical three-body problem, the fundamental construction of molecules, and hydrodynamics, and how to solve such problems on a large computer like NORC. But even this large machine was not as yet capable of competing with a laboratory experiment. The computer still had a long way to go, but it was on its way!

Stellar Positions and Outer Planets

By the early 1950's it became clear that computing would become more and more dependent on the most recent advances in physics, in particular semiconductors for transistors, materials for magnetic recording, quantum optics, particle beams and x-rays for new production methods, and so on. The IBM laboratory at Columbia University was given a new function and a new home to accomodate the new people. Some of them had just completed their Ph.D.'s at Columbia's physics Department, which was at that time the best in the country under the leadership of I. I. Rabi. The new hirees were an unusually talented bunch that was given wide freedom to work in their areas of choice.

Eckert still presided over this hotbed of new activity. But the adjectives "scientific computing" were dropped from the official name of his place; it was called simply the "IBM Watson Laboratory". He was now able to concentrate on his own interests: the application of computers in astronomy in general, and the improvements of lunar theory in particular. The next two sections will try to give a short survey of his further achievements in these areas.

The measurement of stellar positions on photographic plates was an important program under the supervision of Dirk Brouwer, head of the astronomy department at Yale University. Its purpose was to register the data on the plates that were taken at the Yale-Columbia Southern Station. Numerous people were involved, particularly Ida Barney and Dorrit Hoffleit at Yale, and for the numerical processing and automatic scanning, Rebecca Jones and Dorothy Eckert, wife of Wallace Eckert, at the IBM Watson Laboratory.

The plates were taken in the early 1940's at which time many of them were still scanned, measured, and processed visually. The entry of automatic equipment into these time-consuming operations was not at all straightforward, and took longer than some of the participants had wished. But by 1954, the probable error had been reduced to .5 microns in the automatic scanning, which must have been close to the optical resolution in the visible spectrum. The results are published in a series of impressive volumes, some under the authorship of Dorrit Hoffleit "with the major collaboration of Dorothy Eckert, Phillip Lue, Katharine Paranya."¹⁷

Other volumes cover zones between positive declinations, which had been evaluated earlier without the help of an automatic measuring engine. There appeared, however, a net improvement in the accuracy by about 15 to 20 percent in the star's position. A zone 5 degrees wide may typically

contain 10,000 measured stars, each with a position given to .001 time-seconds in Right Ascension and .01 arc-seconds in Declination, as well as various spectral magnitudes and proper motion.

As mentioned earlier,¹³ in collaboration with Brouwer and Clemence, Eckert carried out a direct integration on the SSEC for the trajectories of the five outer planets in forty-day intervals. Although Eckert considered a similar calculation for NORC to be extended over a few thousand years, he didn't find such a project worthwhile for much longer times as long as the orbital elements and masses were not better known. Indeed, one gets into the difficult problems of orbital stability over long times, both in nature and on the computer, a subject that is still wide open.

Lunar Theory

Although this symposium was organized to celebrate the work at the Nautical Almanac Office, one can hardly think of Eckert's life without emphasizing his long-term commitment to lunar theory. It started in 1930 when Eckert helped Brown to check the precision of Brown's solution of the three-body problem Moon-Earth-Sun. They wrote the Cartesian coordinates as a harmonic series in the four standard angles with numerical coefficients, and then used Airy's idea of inserting these series into the (differential) equations of motion to work out the residues. They used the punched card machines of the time, but did not finish the job before Brown died in 1938; also Eckert did not have the leisure to complete the work during WWII.

The continuation of the story is well described and all the further ingredients are given in the form of a Joint Supplement to the American Ephemeris and the (British) Nautical Almanac, entitled "Improved Lunar Ephemeris 1952-1959".¹² Brown's original theory was analytical in all parameters except the ratio $m = n'/n$ of the solar over the lunar sidereal mean motion. In reducing these general expressions to the Tables of the Moon, Brown had made some minor simplifications. The resulting errors had been detected observationally by the Royal Astronomer Spencer Jones in 1939, and Clemence had explained them in 1948. Eckert, Rebecca Jones, and Clark went back to Brown's original harmonic series, which is listed in the Introduction of the Tables, and calculated the lunar Ephemeris directly for the years 1952-1959 with the help of the SSEC. Finally, E W Woolard¹⁸ examined very carefully the differences between the two ephemerides, from the Tables and from the trigonometric expansion over the period of one month.

This work was published in early 1954, and one wonders how many of its many contributors thought that their results would soon become of central importance in the project to send human beings to the Moon. In 1957, presumably before Sputnik, Eckert and Jones decided to check out Brown's lunar theory, not only his Tables, by the method that Brown and Eckert had tried already in the 1930's. The work can be simplified by a trick that goes back to George William Hill: by combining the equations of motion properly, the division by the distance r from the Earth to the Moon can be completely eliminated, leaving only multiplications of large harmonic series to be done. The IBM 650 machine was used.

After an initial report ¹⁹ in 1958, however, the next publication came 7 years later and several others followed shortly thereafter. It is, therefore, difficult to follow up on this project during the busy years when NASA was getting ready for the Apollo program. One would like to get a more precise idea of Eckert's role in these preparations. But all these new papers make only passing reference to any results from either Earth satellites or lunar probes.

At the end of 1965, Eckert reported the efforts to determine the moments of inertia for the Moon. ²⁰ The distribution of mass inside the Earth had meanwhile become much better known from the orbits of the first artificial satellites. But the evidence for the Moon comes entirely from the independent, but equivalent results of Hill and of Brown concerning particularly the motion of the node. The deficit in the centennial motion is quite large, and seems to argue in favor of a model where most of the Moon's mass is concentrated on the surface. The resolution of this obviously untenable conclusion is not clear.

The next paper was written by Eckert and his coworkers M. Judy Walker and Dorothy Eckert. ²¹ It is concerned with Brown's transformation from his original Cartesian coordinates to polar coordinates. First, the small algebraic parameters of the theory are adjusted to fit the observationally most important terms in the harmonic series, and then all the other numerical coefficients are calculated. The longitude and latitude are now determined with a precision of ".0001, and the sine parallax with ".000001, and several new terms are taken into account. The necessary corrections are meant to apply to the list in ILE. The improvement in the sine parallax is carried out for the purpose of the laser ranging experiments.

After this preliminary exercise in getting the best out Brown's work, Wallace J Eckert and Harry F. Smith, Jr. ²² decided to use the most recent

harmonic series for the coordinates of the Moon, and insert them directly into the equations of motion in order to find the corrections in the coefficients that cancel out the residues in the equations. This project goes back to Airy who had worked on it for a long time without completing the task before he died in 1892 at the age of 90. It was decided "to attack the problem on a more ambitious scale, and to improve Brown's coordinates by about two orders of magnitude." The model IBM 7090/94 was used; Rebecca Jones did some of the initial programming, whereas Harry Smith wrote the bulk of the programs and supervised the machine operations. The results were published as volume XIX, part II, of the *Astronomical Papers of the AE and NA*, with more than 200 pages. It is hard to avoid the impression that this project was at the limit of the computing facilities.

The basic method is to find the first corrections to the coefficients by solving the linearized conditions for them. The corrected coefficients are then inserted again into the equations of motion, and a second set of corrections is found. This process is repeated, assuming that it converges, until the residues vanish or the next corrections fall below the desired limits. The series in rectangular coordinates contain about 9,600 terms down to 10^{-12} in units normalized to the distance of the Moon from the Earth, or 2×10^{-7} in angular measure. The solution of the linear equations had to be carried out in well-chosen groups of terms, and requires extreme caution in some cases that correspond to small denominators. But aside from 30-40 terms with a probable error of the order 10^{-11} , only a few terms have an error larger than 10^{-10} . The whole enterprise has the earmarks of a tour-de-force, but "Brown's solution is even better in many respects than he had hoped, and the freedom from error in his work is truly remarkable."

Now that Brown has been proven accurate, Eckert is getting ready to start from scratch by doing first the work of George William Hill on a computer. Of course, the tools have been vastly improved with the use of a general purpose machine (IBM 1620) and the symbolic programming system (SPS). The Hill-Brown method, in contrast to Airy's, is much less demanding on the solution of linear equations. There are no vectors with more than 30 components even at 20-digit accuracy, and the outer components decrease by almost 2 order of magnitude away from the center. Also the book-keeping and ordering of terms is quite rational.

The only record of Eckert's grand new project is a paper dating from the time when he retired, in collaboration with Dorothy Eckert.²³ Basically, Hill's great work is done over again, although the critical ratio $m = n'/(n-n')$, i.e., the length of the synodic month over the sidereal year,

is always kept numerical rather algebraic. The calculation, however, is done for 3 different values of m so that interpolation of the results for the best empirical value is possible. Also, both mass ratios, Moon/Earth and (Earth + Moon)/Sun, are used from the very beginning. Four different values are used for the latter, including 0. Only Hill's variational orbit is calculated as well as the first-order corrections that yield the motion of the perigee and of the node. Needless to say that all the decimals check with Hill's work.

From this starting point Eckert planned to compute all further corrections in terms of the other 4 small parameters that are kept algebraic, eccentricity and inclination of the Moon's orbit, as well as the eccentricity of the Earth-Moon's orbit around the Sun and the ratio of the semi-major axes a/a' . All the terms were to be calculated provided the combined exponent did not exceed 6. The corrections to the motion of the perigee and of the node are obtained from certain consistency conditions at the odd exponents. Brown's program was done again in a more sweeping and ambitious form, and for different numerical values of m and the mass ratios.

When Eckert became fatally ill, his programmer Sarah Bellesheim had successfully completed the second-order terms and was working on the third order. Although not an astronomer, she knew exactly what had to be done; Eckert had been a good teacher. The work was completed in early 1975. The further story is told in the introduction to a paper by the author²⁴ and in a full report with discussion, by the author and Dieter Schmidt.²⁵ First, the results of Bellesheim were transformed into polar coordinates, a direct comparison with two entirely different calculations by Deprit and by Henrard²⁶ were carried out, and found very satisfactory. But then, the whole work was done over again by Dieter Schmidt²⁷ using somewhat different programs and defining the bounds for the project differently. Instead of computing all sixth-order terms many of which are negligible, limits were set by the size of the terms. That meant going as far as order 10 in a few cases so as to get all the terms larger the 10^{-12} in Cartesian coordinates. The harmonic series for the polar coordinates were obtained and listed as well as their derivatives with respect to the main parameters, including m , so as to allow for future changes in their empirical values. It is published in the *Astronomical Papers of the AE and NA*, vol. XXIII.

Epilogue

Wallace J Eckert belongs to the remarkable generation of American scientists who were born around the turn of the century. They grew up during WWI, they got their education not only at the elite universities, but also in the smaller liberal arts colleges and state universities, and they started their scientific work in the late 1920's and early 1930's. Unbeknownst to the rest of the world, and maybe to themselves, they moved the United States ahead of the traditional centers of science, in Great Britain, France, Germany, the Netherlands, Scandinavia, and so on.

By the late 1930's Eckert had tried out his pioneering approach to celestial mechanics, he knew exactly what to concentrate on and how to get it done. Through his leadership at the Nautical Almanac Office and the efficient production of the Air Almanac he made a major contribution to the war effort. Then he had a unique chance to give the IBM Corporation the benefit of his experience in using automatic data handling equipment in the sciences. During all this time he pursued his own goals in astronomy, particularly in the theory of the motion of the Moon where his expertise again was important for the success of the Apollo program of NASA.

In spite of all these marvelous achievements Eckert remained an individual without the slightest trace of pretense. His ideas were clear and his judgement was always well-founded and straightforward. He got a moderate amount of official recognition such as the Craig Watson medal in 1966 from the US National Academy of Sciences. But his modesty may have been deceptive to his collaborators and the public because some of these rewards came late in his life, like the nomination as an IBM Fellow one month before his retirement and a special Outstanding Contribution Award two years later.

At the Memorial Service for Eckert, his long-term colleague at the physics department, I.I. Rabi, called him a 'true pillar' among the faculty of Columbia University. John Ashbrook, in his obituary ²⁸ in *Sky and Telescope* "A Great American Astronomer" says: "Hardly any other astronomer of his generation influenced our science more profoundly."

NOTES

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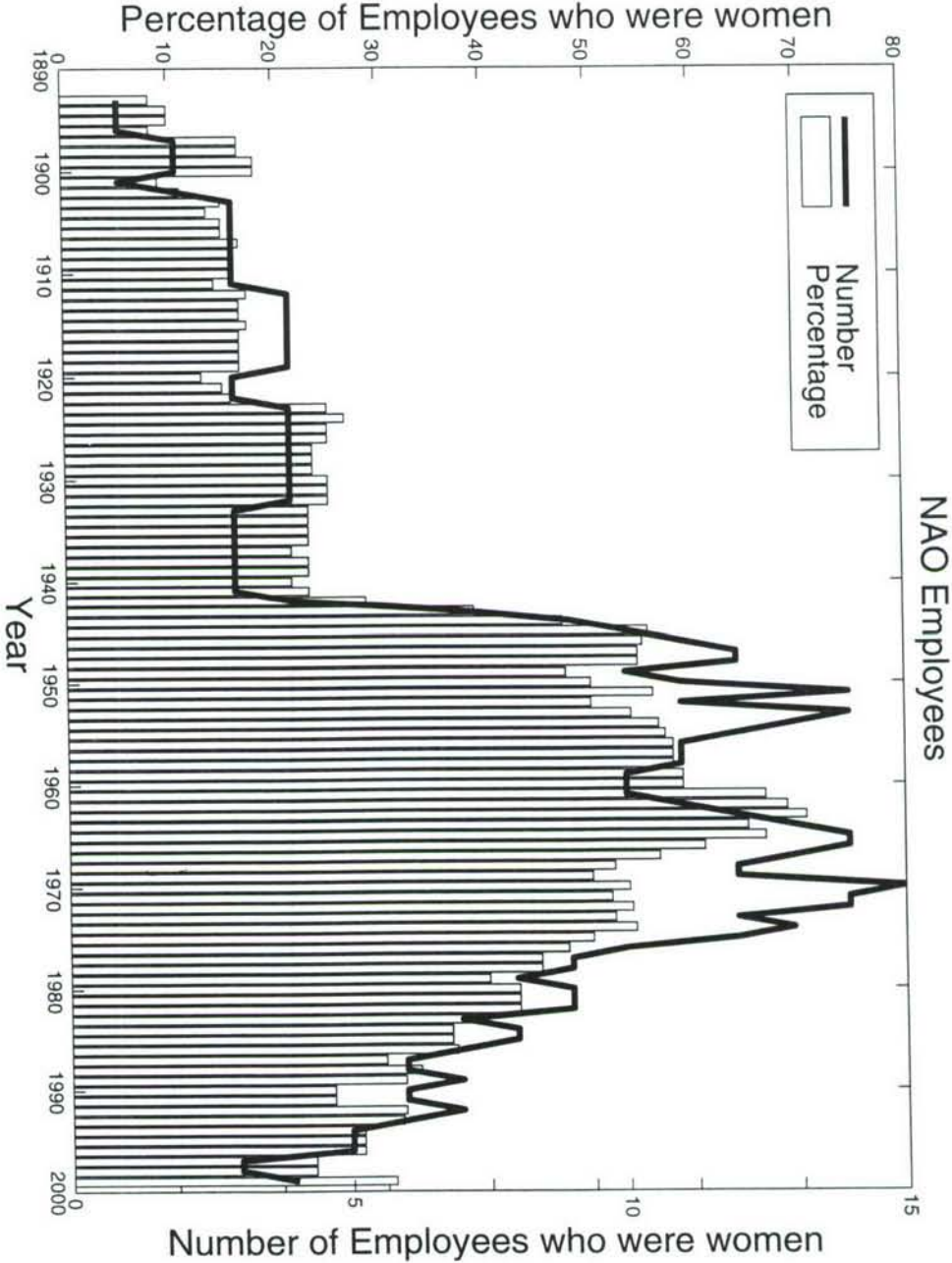
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THE CONTRIBUTIONS OF WOMEN TO THE NAUTICAL ALMANAC OFFICE, THE FIRST 150 YEARS.

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Introduction:

The American Nautical Almanac Office (NAO) was founded in 1849, and it was in the same year that its first woman employee was hired. Forty-four years later, the doors were opened to a second woman employee, and from then on, women have been continuously included in the office. This paper highlights the lives and contributions of a few of these women. The women included in this paper were chosen because we were able to obtain good, documented information on their lives and contributions. They tend to be long-term employees, in mid-level jobs, however it should be noted that these women do not fully represent all of the female employees in the Office. A listing of the names of all women employees is included at the end of this paper.

In general, we see that the first women employees were women who were outstanding in their field. Generally they were highly educated, and often considered mathematical prodigies. Some of these women worked from home, as pieceworkers, however the majority were regular members of the office. World War II brought many changes to the NAO, and as the nature of the work evolved, so did the background of the employee. Almanac production became more automated, more women were hired, however they were concentrated in routine jobs such as card punching and error checking. After an all time peak in 1963, the percentage of women in the office began to decline.

Today's smaller workforce includes women of diverse backgrounds to meet the challenges of future almanac development and production. Figure one illustrates both the number of women employees and the percentage of the total number of employees who were women from 1890 to 1999. It should be noted that since 1990, the NAO has been a division of the Astronomical Applications (AA) Department, therefore all the women in the AA department have been included in the figure.

The early years:

Maria Mitchell, one of America's most famous woman astronomers, was the NAO's first female contributor. Maria Mitchell was born August 1, 1818 in Nantucket, Massachusetts. Her interest in astronomy was fostered by her father who ran a school and allowed Maria to observe with a telescope he had positioned on the roof of their home, as well as to assist him while he rated chronometers. In October 1847 she discovered a comet, for which she was awarded a gold medal by the King of Denmark.

In 1849, she was appointed a "computer" for the American Ephemeris and Nautical Almanac. She completed computations associated chiefly with the planet Venus for 20 years. She received and returned her assignments through the mail. In 1865, she became a professor of astronomy and director of the College Observatory at Vassar College in Poughkeepsie, New York. She conducted research on the Sun, Jupiter, and Saturn as well as astrophotography¹.



Maria Mitchell

The American Ephemeris and Nautical Almanac for the years 1893 and 1894 credit a "Mr. E. Davis" for computing the ephemeris of the Sun. In fact, we know that it was Mrs. Elizabeth Davis who was responsible for that work. Mrs. Davis was a former employee of Simon Newcomb, who had earned a position earlier the same year with the Nautical Almanac Office. An article highlighting her accomplishments in the newspaper indicated:

*"She competed with a number of men mathematicians for a high place in the Nautical Almanac Office and routed them all in three hours. In two more she had solved all the difficult problems of higher mathematics and astronomy submitted to her, was pronounced by the enthusiastic examiners 100-100, more than perfect and got the place."*²



Elizabeth Brown Davis

Mrs. Davis was born Elizabeth Preston Brown in 1863 in Front Royal, Virginia and graduated with a BS from Columbian University (now George Washington University) in Washington, DC. She did her post-graduate work at Johns Hopkins University in mathematics by special permission of the faculty, which allowed her to study, but not receive a degree. She became a computer in the NAO and assisted in the preparation of Newcomb's Tables of the Sun and Planets. Miss Brown married Dr. Arthur Powell Davis, on June 20, 1888. Dr. Davis was the chief engineer of the U. S. Reclamation Service. Dr. and Mrs. Davis had four daughters, Rena, Florence, Dorothy, and Elizabeth. Mrs. Davis was a member of the American Mathematical Society³, Circolo Matematico di Palermo, and the Auxiliary Board of Regents of Trinity College. Mrs. Davis was listed as both an assistant, and a piecemaker for the NAO in the annual reports of the observatory. She did other miscellaneous work on comet orbits, and proof-reading of textbooks on mathematics,⁴ and enjoyed writing magazine articles on mathematical subjects.⁵ Mrs. Davis died on April 13, 1917.

Miss Ellen A. Hedrick, daughter of Benjamin Sherwood Hedrick, a former Nautical Almanac Office employee, was the third woman employee. She worked with her brother Henry Benjamin Hedrick on the mean and apparent places of fixed stars. Miss Hedrick was employed with the NAO from 1897 to 1900. After leaving the NAO, Miss Hedrick worked as a librarian at the Library of Congress, Yale University, the University of California, and the U. S. Department of Agriculture. Miss Hedrick died December 10, 1957.⁶

The 1902 Almanac indicated that a fourth woman, Hanna Fancher Mace Hedrick had joined the staff. Miss Mace was born in Walton, New York on January 9, 1870. She graduated from Vassar College with honors in 1890. She took a short break from her own studies to teach from 1890-92. She then continued her studies at Vassar as a fellow in mathematics from 1892-93 and moved to Yale University graduate school where she

was Phi Beta Kappa and Qui Vive as a scholar in mathematics from 1893-1894. In 1894 she began her lengthy yet somewhat erratic career as a member of the Nautical Almanac Office (NAO). Her career was complicated by the fact that on April 30, 1896 she married fellow NAO employee Henry Benjamin Hedrick, who was with the NAO from 1886 to 1908. The Hedrick family left Washington for Yale in 1909 where he worked as an assistant astronomer until 1918 receiving his Ph.D. from Yale in 1915.

Mrs. Hedrick continued with the NAO as a pieceworker, but completed most of her work via correspondence in much the same fashion that Maria Mitchell did many years before. At the time of her retirement in 1940, she was working on tables of stars that would be occulted by the Moon. The Hedricks were also the parents of three children, Benjamin Mace, Anna Fancher, and Eleanor Thompson. Aside from her mathematical work for the Naval Observatory, Mrs. Hedrick was interested in the development of children as well as scientific efficiency in the home. Hannah Hedrick enjoyed riding, driving, rowing, hunting, and tennis, and favored women's suffrage.⁷ Hannah F. M. Hedrick died February 26, 1958, at the age of 88.⁸

In 1923, the Almanac lists Catherine de Mille Lewis as its first woman employee in the position of "Assistant", the title was changed to "Jr. Astronomer" the following year. Miss Lewis was the daughter of Frank Rockland and Mary Germaine Lewis. She was born June 24, 1888, and received an A.B. degree cum laude in 1910 from Radcliffe College. Though she indicated that she had studied with the intention of becoming a teacher,⁹ she went to work cataloging for the New York Public Library system, then as a filing and indexing clerk for the Library Bureau Service in the Ordnance, War Department. In 1919 she arrived at the NAO where she worked for eight years. She left the Office and accepted a position with the Library of Congress as



Catherine de Mille Lewis

an assistant cataloger and remained there until her retirement in 1953. She did graduate work at Catholic University of America in Irish, Coptic and Arabic, as well as work in Spanish and Italian at George Washington

University. Her main interests were literature, gardening, historic homes, and bird-lore. She published a book of poetry in 1954 called *A Wilderness of Song*, and a burletta in 1930 called *The Caliph Stork*.¹⁰ Catherine Lewis died September 27, 1960.¹¹

Mrs. Isabel Martin Lewis is listed in the 1933 Almanac as the first woman with the prestigious title of "Astronomer". She was born in Old Orchard Beach, Maine, on July 11, 1881. She received her A.B. from Cornell in 1903 and her A.M. in 1905 specializing in mathematics. In 1904 she taught school in Summit, New Jersey. Miss Martin became a computer for Prof. Simon Newcomb in 1905 and learned to work on eclipse data under his guidance, a task which her fellow employees recall her as being "very fine at".¹² Miss Martin worked for Newcomb until 1907. A few months of this duty included work for the Naval Observatory as a miscellaneous computer.



Isabel Martin Lewis. Courtesy of the Robert W. Lewis Family.

In 1908 Miss Martin was hired in the NAO and listed under "Assistants and Employees". On December 4, 1912 she married Clifford Spencer Lewis who was also with the Office. In accordance with the rules governing civil service employment, only one family member could work full time in the same organization, and Mrs. Lewis became a part-time piecework computer working from her home. While working part-time, Mrs. Lewis published three books. The first in 1919 entitled "*Splendors of the Sky*" and the second in 1922 was "*Astronomy for Young Folks*". Both of these books are written on the popular astronomy level, and reveal her strong interest in educating the public and especially children to the wonders of astronomy.

Lewis' third book was "*A Hand Book Of Solar Eclipses*" which was published in 1924. This book had one and a half chapters devoted to the eclipses of January 1925, and June

1927, but most of the book was focused on the phenomena which accompany a solar eclipse and therefore has remained a valuable resource even today. Chapter six of this handbook gives the reader valuable insight to the work of an astronomical computer. Here we learn that an experienced computer could perform the necessary computations for a total eclipse of the Moon in two working days of 7 hours each. A total solar eclipse would be much more difficult and that, to assure accuracy, two computers would work on the calculations using different methods. The check performed on these calculations alone took Mrs. Lewis between ninety and one hundred and twenty hours of "exacting work", and she had the responsibility of making the check computations for most of her career. The fact that Mrs. Lewis described this task as a privilege is testimony to her devotion to duty.

After the death of her husband in 1927, Mrs. Lewis returned to work full-time and was promoted to Assistant Scientist followed by a second promotion to Astronomer in 1930. Her contributions to the NAO included a new method which she developed to calculate the northern and southern limits of visibility for an eclipse which was more accurate and required less time and labor than the previously employed method. She devised a procedure to increase the number of lunar occultations predicted in the Almanac when they became more important for investigating the motions of the moon. She developed the formulae for computing solar eclipses at the altitudes needed to investigate ionospheric phenomena. She improved the current method for correcting eclipse predictions at one location so that a prediction could be obtained for a nearby location. Later in her career when the NAO was upgrading to electric calculating machines, Mrs. Lewis adapted and improved the existing equations for that transition.¹³

Through her whole career Mrs. Lewis was a prolific writer and published articles in *The New York Evening Sun*, *Science and Invention*, *Popular Astronomy*, *The Astronomical Journal* and many others. For thirty years Mrs. Lewis had a regular monthly series of articles published in *Nature Magazine*. Her editor noted that "She had an abiding respect for deadlines. Her articles were clear and concise." He also took the liberty to add that "She was mighty sweet too."¹⁴ She gave lectures on the local National Broadcasting Company radio station (WRC), and traveled to local schools and churches to give presentations to the children.



Isabel Lewis (Center). Photo courtesy of the Robert W. Lewis Family

Isabel Lewis specialized in eclipses, she was a member of eclipse expeditions to Russia in 1936, and to Peru, in 1937.¹⁵ She organized her own expedition to Honeylake California in 1930 to view a total solar eclipse which particularly interested her because it had a totality of only 1.5 seconds. Of this eclipse she said *"Considering the difficulties of the problem, it might seem futile to travel across the continent and stake one's chances on securing, within a path only 5/8 of a mile wide, a photographic exposure of only 1 second's duration, all to test out the accuracy of an astronomical prediction and the correctness of the data upon which it was based. Yet the very difficulties of the problem made it attractive."*¹⁶

In 1918 she was elected a member of the American Astronomical Society. She was also a member of the Astronomical Society of the Pacific, and the Royal Astronomical Society of Canada. Mrs. Lewis retired from service at the Naval Observatory in 1951 but continued to publish in newspapers and magazines until 1955. Isabel Lewis favored women's suffrage and enjoyed walking, swimming, skating, rowing, and tennis. She opposed the use of animals in scientific experiments and supported all efforts to prohibit it.¹⁷ Mrs. Lewis was described by one of her colleagues as "One of the staunch workers in the office until the time of her retirement." As well as "Unquestionably intelligent" and "Very capable in an era when women were given a very minor role in astronomy."¹⁸ Isabel Martin Lewis had one son, Robert Winslow Lewis. She died July 31, 1966.¹⁹



Berenice Morrison, Victoria Meiller, and Jean (Hampton) Dudley. Photo courtesy of the Naval Observatory

The Current Almanac credits four women with contributions to its completion: Yvette Holley, Wendy Hultquist, Marie Lukac, and Dr. Susan G. Stewart. Susan Stewart became a member of the office in 1997. She received a B. S. in Physics and Astronomy from Vanderbilt University in 1990, and a Ph.D. in Physics from the University of Alabama in 1998. Her research focused on star formation in irregular galaxies and ultraviolet astronomy. She is currently responsible for maintaining the production schedule of the NAO's annual publications.²⁷ Dr. Stewart is the first woman NAO employee with a Ph.D.

The following is a list of women who are know to have contributed to the publications of the American Ephemeris and Nautical Almanac, or one or more of the publications of the Nautical Almanac office since its inception in 1849. The list includes women of all job titles, and we have made an effort to list each woman only once, although she may have worked under one or more names.

Carla L. Anderson
Candice P. Baines
Rubye M. Barnes
Josephine D. Beasley
Sally J. Bensusen

Helen F. Beyke
Joan Ellen Bixby
Jean A. Blake
Lena G. Clopton
Jacqueline M. Coehins

Grace E. Combs
 Phyllis Cook
 Theresa E. Cooney USNR(W)
 Georgianna W. Council
 Elizabeth B. Davis
 Susana Deustua
 Diane Diggs
 Mary Ellen Donfor
 Jean B. Dudley
 Julena S. Duncombe
 Geraldine C. Faerber
 Lillian Feinstein
 Linda Gardner
 Marta R. Goldblatt
 Simone Daro Gossner
 Constance S. Graleska
 Loretta Green
 Helena Guertler
 Martha P. Hasenstab
 Barbara A. Hawley
 Joy Heckathorn
 Ellen A. Hedrick
 Hannah F. M. Hedrick
 Vivian M. Holland
 Blanche R. Hollander
 Yvette Holley
 Wendy K. Hultquist
 Elizabeth B. Jackson
 Charlotte S. James
 Gertrude E. Jamison
 Wanda L. Jenkins
 Gertrude L. Johnson
 Patricia A. Joseph
 Margaret C. Keeffin
 Ki Ok (Christine) Kim
 Charlotte Krampe
 Marion E. Lauris USNR (W)
 Lou Ellen Leech
 Catherine de M. Lewis
 Isabel M. Lewis
 Louise B. Long

Marie R. Lukac
 Jean F. McCormick
 Sharon C. McInnis
 Barbara H. McMorris
 Janet McWilliam
 Victoria Meiller
 Helena Meltesen
 Ruth L. Meyers
 Mary H. Mikesell
 Maria Mitchell
 Carolyn F. Moore
 Berenice L. Morrison
 Betty Kendrick Murphy
 Carolyn Murphy
 Elma Kaasala Oehrtmann
 Mary Ann Phillips
 Jackie S. Potts
 Otavia Propper
 Ida E. Ray
 Edith F. Reilly
 Jeannette Reuning
 Mary Euston Ridgely
 Gretchen M. Robenhymer
 Irene F. Roberts
 Alden J. Rodgers
 Shelley Rogers
 Nettie Rotunno
 Laura E. Schombert
 Mary Patrice Schuette
 Joyce A. Schwartzmann
 Barbara D. Scott
 Marian H. Sharpless
 Beverly Slater
 Helen V. Smith
 Tecla Combariati Smith
 Marion Sosslau
 Mildred A. Spriggs
 Doris B. Stanley
 Anna K. Starsinic
 Lula M. Stephens
 Susan G. Stewart

Lillian E. Strong
 Rosa E. Trainham
 Mable L. Vandergriff
 Diana R. Wagner
 Jennifer J. Weeks
 Louise B. Weston

Catherine S. Williams
 Elsie V. Willis
 Judy P. Wise
 F. Neville Withington
 M. Helen Wright

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A BRIEF SURVEY OF MODERN NAVIGATION

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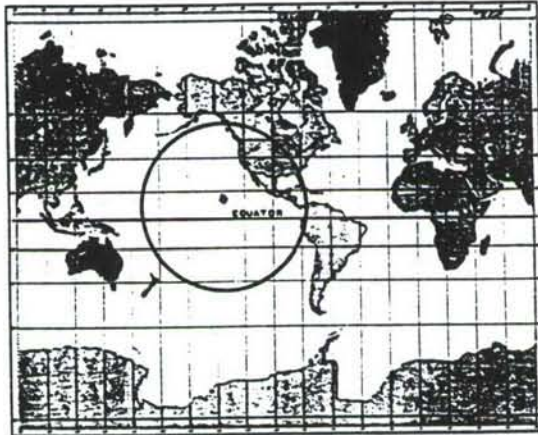
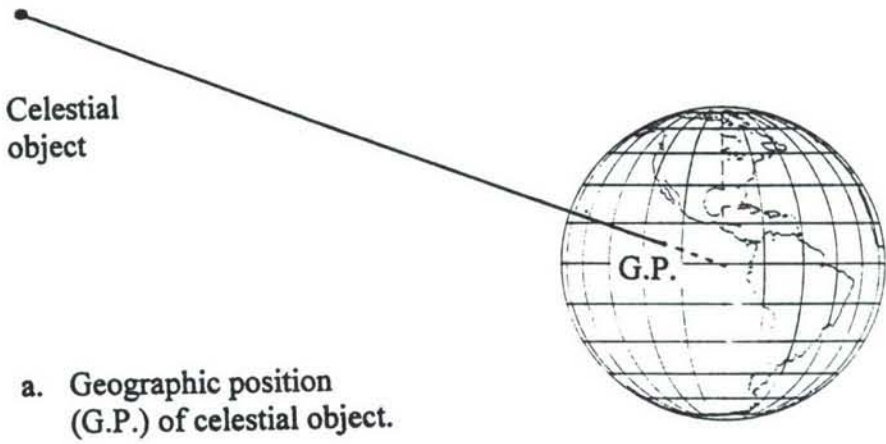
Introduction

There are many forms or systems of navigation that may be called modern. To qualify as a brief, a survey must be based on some limiting criterion. Here I propose first to consider some basic principles associated with all modern navigation and then to limit descriptions of individual navigation systems to a very few that fit into the first of two broad divisions. The first division is absolute navigation, wherein present position is known in relation to an overall coordinate system (latitude and longitude, for example). The second is relative navigation, wherein present position is known relative to some local, special coordinate or grid system. The difference between divisions may be thought of in terms of global versus local. As an example that qualifies as absolute, the Global Positioning System (GPS) is probably the best known. Using road maps or landmarks are everyday examples of relative navigation, as are Very high frequency Omnidirectional Range (VOR) systems used by aircraft as highways in the sky.

Before continuing, a few points should be noted.

- While navigation involves directing vehicle motion safely and efficiently from one location to another, key words in both absolute and relative navigation are "present position is known." Therefore, it is understandable that effort to devise methods, devices and systems has been concentrated on determining vehicle present position.
- For modern systems, the distinction between absolute and relative can become blurred. Soon, for example, we will likely find GPS officially approved and used for both relative and absolute navigation.

As representative of modern navigation by means of modern systems, I will describe briefly and with some arbitrariness, Loran-C, Omega, inertial, Transit and GPS. Omega and Transit are discontinued. They are nevertheless modern and I will describe them as still active.



c. Intersecting
position
circles.

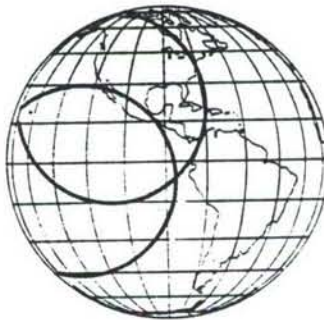


Fig. 1. Position finding by angle observations of celestial objects.

Basic Principles

A few basic principles are common to all modern navigation. It is worthwhile to examine those principles in a little detail.

The first principle is that of a position line. It was first introduced into open ocean navigation in 1837, by way of celestial navigation. To understand a position line requires only the ability to visualize some simple geometry on a sphere.

In Figure 1a, a line is drawn from the center of the Earth to a celestial object (Sun, Moon, star, planet). The line intersects the surface of the Earth at a point. At that point on the Earth, the object is directly overhead, and that point is called the geographic position (G.P.) of the celestial object. The geographic positions of celestial objects, especially those useful to navigation, can be calculated to very high accuracy for any specific time, well in advance of that time.

In celestial navigation practice, a device to measure angles is used to determine the angular distance of a celestial object from the horizon. At the instant the measurement is made, the object has a definite geographic position, as described above. The measured angle then defines a line on the Earth; the line having the property that at any point on it the celestial object will have the same angular distance from the horizon. We call the line a line of position. It has another interesting property. It closes on itself to form a circle. The importance of the position circle is the fact that the navigator's position is somewhere on that circle. Figure 1b shows the position line, or position circle. It also shows lines of latitude and longitude, and it can be seen that the position line intersects any number of latitude and longitude lines. As a result, a navigator needs additional information in order to determine known position. The additional information comes from making an angular measurement of another celestial body to produce a second position line, as shown in Figure 1c. The two position lines intersect in two places and the navigator's position is at one of the intersections. With celestial objects carefully chosen, the navigator can produce large position circles (lines) that also intersect at large angles, and can thereby decide which intersection actually represents his position.

The second principle is the precisely known, constant velocity of electromagnetic radiation in all directions in a uniform medium. It is a physical constant expressed as miles per second, or as kilometers per second. The fact that radio waves, in particular, travel at constant speed, and do so in all directions is basic to modern radio navigation. In simplest

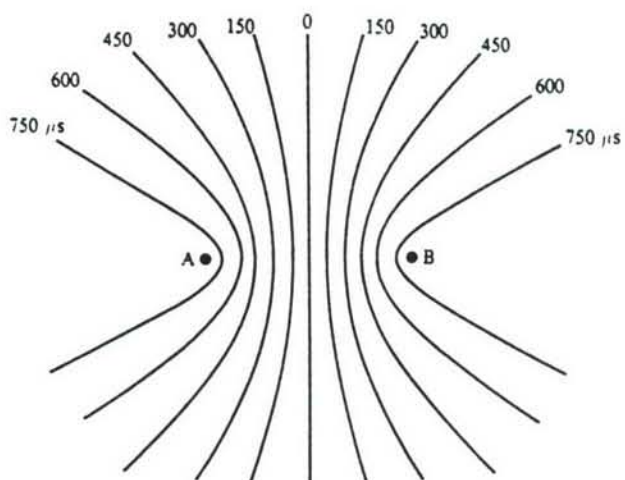


Fig. 2a. Hyperbolic position lines generated by measured time differences.

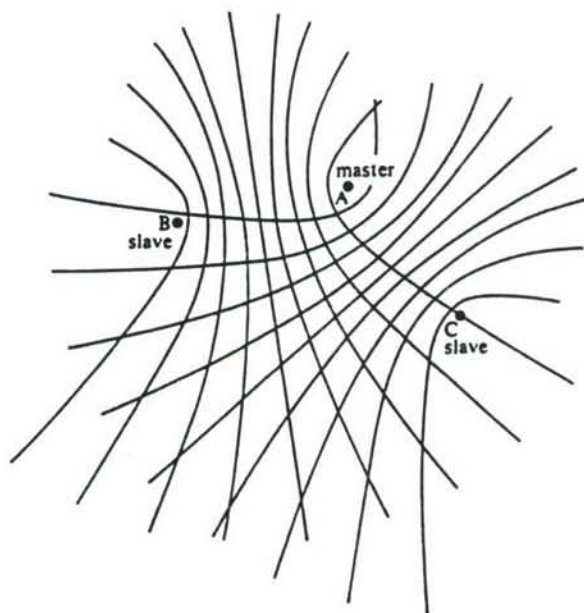


Fig. 2b. Two hyperbolic patterns obtained from three transmitters.

form, a radio station transmits a brief signal. A navigator has a receiver and an accurate clock that is synchronized with the clock at the radio station. By using the clock to know when the radio signal was sent, and by measuring the interval of time for the signal to arrive at the receiver, the distance to the radio station can be determined. However, the radio station sends the signal in all directions. Consequently, knowing the time interval, or distance, simply places the navigator on a position line similar to what was seen as basic to celestial navigation. The only difference is that the radio transmitter is physically located at the center of the position. Additional information is required and is supplied by a second transmitter, at some distance from the first and with its clock likewise synchronized. Again, the navigator's position is determined by the intersections of the position circles. In straightforward application, this method requires receivers coupled to atomic clocks. Atomic clocks are very expensive, need periodic calibration and, ultimately, replacement.

A simple technique avoids the need for an atomic clock in every receiver. Two radio stations transmit precisely synchronized signals. Then, instead of measuring absolute time of arrival, a navigator only needs to be able to measure the difference between the arrival times of both signals. Fortunately, by using relatively inexpensive clocks (or oscillators) in navigation receivers, this is possible. But, in this case, a constant time difference between two signals, rather than precise times of arrival, locates the navigator somewhere on a position line that is an hyperbola, as in Figure 2a (time differences are labeled in microseconds). A third transmitter, also synchronized, is required. The receiver can then measure a time difference between the third signal and either the first or second signal. This gives rise to a second hyperbola representing constant delay time difference. As in the case of intersecting position circles, the intersecting hyperbolas (Figure 2b) can determine a unique latitude and longitude. Used in this way, Loran-C and Omega qualify as hyperbolic systems. Clocks in receivers do not have to be synchronized with those at the transmitters, but only need to be stable for short intervals of time.

It has been said that signals from radio navigation transmitters travel outward in all directions. When considering the measurement of time delays of signals from far above Earth's surface, the geometry of position lines becomes what mathematicians call hyperboloids. We need not explore that geometric fact here, but the omnidirectional characteristic has made possible the use of hyperbolic radio navigation aboard aircraft as well as on Earth's surface.

When radio navigation transmitters are located in spacecraft, rather than on the ground, there is no great distinction to make in regard to geometry, only a reorientation. The signals again travel outward from a spacecraft in all directions. For navigation on the Earth's surface, the distance to a satellite is measured by determining the time taken for a signal to leave the satellite and arrive at the navigation receiver. In this case, a single distance measurement to one satellite locates the receiver on a line of position of the exactly same type as encountered in celestial navigation. The main distinction is one of angular measurement versus distance measurement. As in celestial, it takes a separate measurement to a second satellite to create intersecting position lines that determine position. The technique to overcome the problem of maintaining a very accurate clock within a navigation receiver is discussed below.

Another physical principle that has been basic to a navigation system is the Doppler effect. Simply stated, the frequency shift of received electromagnetic radiation depends upon the relative motion of the source, the receiver, or both. The geometry leading to a determination of position is not intuitive, and use of the principle as the basis for navigating ships or aircraft is practical only if the source of the waves, specifically radio waves, has sufficient velocity to cause an easily measured frequency shift. An artificial satellite answers the need. The U. S. Transit and Russian Cicada navigation systems were constructed to use the significant frequency shift produced in radio signals transmitted by orbiting satellites, but primarily for ship positioning.

All of the principles described so far, when applied to navigation, have in common an external source of radiation, whether the light of a celestial object or radio signals. A system that does not depend on external sources is desirable for several reasons. Such systems have been referred to as self-contained. The most familiar self-contained systems make use of the principle that I state simplistically as: the axis of spin of a spinning rigid body always points to a fixed point in inertial space, absent external forces. An obvious example of such a spinning body is a child's toy top. As adapted for navigation the spinning body is called a gyro. The ensemble of gyro, required sensors, mounting, etc., is called an inertial system. When the gyro is located in a vehicle that is in motion, forces act on it. The magnitude, direction of the forces, and length of time that they act are sensed and measured. The measurements can be used either to apply forces that counteract vehicle motion or restore the orientation of the gyro, or they can be converted to indicate changes in vehicle position and

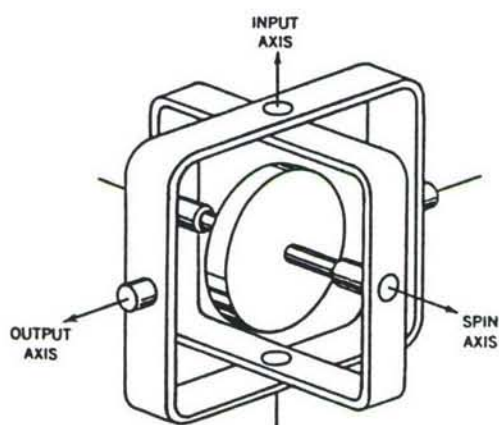


Figure 3. Two-degree-of-freedom gyro without sensors, mounting, etc.



Figure 4. Intersections of three position lines before and after clock corrections. See descriptions of Omega and Global Positioning System.

displayed to the navigator. Figure 3 is a simplified diagram of a two-degree-of-freedom gyro, without sensors, to illustrate the basic device.

The great importance of inertial navigation arises from the fact that an inertial device responds to only to forces acting upon its host vehicle. It is completely self-contained and independent of external signals such as light or radio waves. Because of that importance, inertial systems are now to be found not only on ships and submarines, but also in aircraft, rockets, spacecraft and even in land vehicles. The Ship Inertial Navigator System is one example; the series of Carousel units found in aircraft is another.

During the last 30 years inertial devices have been built that do not use a mechanical spinning body. However, they do retain the "self-contained" characteristic and can operate without reference to stars or radio waves.

Modern Systems

Despite the simplicity of the underlying principles described above, any attempt to implement a system brings additional physical principles to bear. In the real world, neither light nor radio waves travel in straight lines or with unchanging speed when the mediums through which they pass differ. The actual shape of the Earth changes the elegant position circles and hyperbolas into more complex figures. Measuring instruments introduce errors, etc. Table 1 is provided as an indication of physical, geometric and other problems that must be accommodated by modern navigation systems. Problems inherent to celestial navigation are included for comparison. The table is an admittedly incomplete compilation. Space does not allow definition and discussion of every tabular entry; nevertheless some general points should be made.

- The entries are a mix of phenomena and problems that have been completely or partly overcome by the systems, or remain.
- The appearance of the same words in more than one column does not necessarily represent the same problem. For example, the ionosphere affects Omega in a different manner than it affects GPS or Transit. Also, refraction is considered and dealt with as it affects satellite signals differently than in case of celestial.

Loran-C

Loran-C radio stations broadcast precisely structured and timed signals. To create the geometry of useful hyperbolic position lines, three stations, separated by hundreds of miles are required. One station is

designated Master, the remaining two or more are called Secondaries, or Slaves. A group of such stations is referred to as a Chain. The master station signal is a sequence of nine pulses. The signal from the master station is received by a navigator and by the secondary stations. After a short, defined time interval, one secondary transmits the same signal, minus the ninth pulse. Other secondaries continue the pattern until all stations in the chain have transmitted.

One of the primary qualities of a Loran-C signal is its pulse shape. The pulse shape, combined with a technique called phase reversal, allows a receiver to reject unwanted signals reflected from the ionosphere. Such skywave signals would otherwise confound a receiver's conversion of time differences to position lines. The pulse shape must be carefully structured at the transmitter and the receiver must be able to identify it and select the third cycle within a pulse.

A state of the art Loran-C navigation receiver will perform several functions. Among them are: automatically locate and track the selected master and secondary stations, automatically measure time differences, indicate when a signal is lost, attenuate interfering signals, convert time differences to lines of position, and display latitude and longitude.

At this time, all respectable receivers incorporate corrections for the primary and secondary phase factors. But the additional phase factor can still cause problems. It arises from the passage of signals over terrain composed of both land and water. Further, it is a seasonal effect. Consequently, corrections incorporated within receivers may not be accurate, especially when operating within 10 miles of a coastline.

Loran-C can provide a user with position accuracy of about 0.25 nautical mile. The system is useful to a distance of 1200 nautical miles (nmi), but waves reflected from the ionosphere can increase coverage to 2300 nmi with a reduced accuracy. The system has been so successful that chains have been built to cover most of the Northern Hemisphere.

Omega

Omega (nominally 10 kilohertz) signals can reach virtually any location using only eight transmitters. Worldwide coverage is obtained by taking advantage of the fact that very low frequency radio waves tend to follow Earth's curvature and can be received at enormous distances. Omega position determinations are not as accurate as with Loran-C, but adequate for enroute navigation on or over open ocean. Each Omega transmitter operates independently of the others, but the transmissions are

Table 1. Physics and Geometry Affecting Performance and Accuracy

<i>Loran-C</i>	<i>Omega</i>	<i>Inertial</i>
Phase:	Signal propagation mode:	Alignment
Primary	attenuation rate	Bias
Secondary	excitation factor	Coriolis "acceleration"
Additional	phase velocity	24 hour oscillation
Ground vs. sky waves	Ionosphere:	Schuler oscillation: 84 m.
Station (clock) sync	day / night	Gravity anomalies
Envelope / cycle match	sudden disturbance	Vehicle:
Crossing angle	polar cap disturbance	roll
Interference	latitude	pitch
Receiver:	Ground conductivity:	yaw
oscillator	normal / ice caps	acceleration
3 rd cycle ID	Arctic	Analog / digital converter
cycle match	aurora	Reset / update
other circuitry	Antipode phase confusion	Other electronics
Fix ambiguity	Geomagnetism (East-West)	
	Lane slip	
	Lane ambiguity	
	Receiver quality	

synchronized by atomic clocks at the stations. Every station transmits on four common frequencies, and each also transmits on its own unique frequency. No two stations transmit on the same frequency at the same time, so there is no overlap. But because of the multiple frequencies and stations, information flowing to an Omega receiver is almost continuous. At any receiver location and time, most of 40 possible signals are useable. Basically, a receiver measures a phase difference between signals from three or more stations to produce hyperbolic position lines and a position.

However, it is also possible to use Omega in direct ranging mode, also called range-range mode. For this mode, a receiver generates a reference signal that replicates the actual Omega signal. As the real signal is received, the replica is shifted in phase until it coincides with the real signal in the receiver circuitry. The phase shift is equivalent to a time interval, which equates quite simply to distance as

$$\text{Distance} = \text{velocity of light (radio)} \times \text{time interval.}$$

The distance measurement is interpreted as defining a circle of position, as described above. Repeating the process using a signal received

Table 1. *Continued*

<i>Transit</i>	<i>GPS</i>	<i>Celestial</i>
Refraction: ionosphere troposphere	Refraction: ionosphere troposphere	Personal equation Sextant: (7 error sources) Height of eye
Height: geoid at vehicle positions vehicle antenna	Height: geoid at vehicle position vehicle antenna	Refraction: air temperature atmos. pressure inversions
Chart congruence	Chart congruence	Cloud cover
Velocity: satellite vehicle Earth	Multipath reflection System clocks Ephemerides quality Message quality Satellite geometry Receiver type: access capability correlation ability	Horizon: night false
Position estimates		Object: semidiameter phase parallax
Satellite crossing		Time
Ephemeris quality		Estimated position
Message quality		Geoid
Satellite geometry		Calculation accuracy
Receiver & computer		Position line geometry

from a second station defines a second position circle. Ideally, the receiver must be located at one of the two points where the position circles intersect.

Two measured distances and position circle intersections are suspect. That is because the velocity of light is so great that a very small clock error can produce a large distance error that carries over into latitude and longitude. A simple technique borrowed from long-standing celestial navigation practice takes care of the situation. A range to a third station is measured and a third position circle is generated. The three position circles do not generally intersect at a point (Figure 4). The receiver clock is then adjusted by a constant amount, which causes changes to the phase values, distances and position circles. This adjustment process is repeated until all position circles do intersect at a common point, hence an accurate position.

State of the art technology has benefited Omega receivers, as it has for Loran-C. All of the circuitry and computations implied by the above descriptions, from signal reception to direct display of latitude and

longitude, can now be carried out automatically. It is no longer necessary, for example, to plot lines on specially printed charts when using either system.

Inertial

For many years the spinning gyro, as a navigation device, had the limited capability of indicating heading of a ship. Called a gyrocompass, it could be considered a navigation aid. An inertial navigator requires some mechanism to sense the forces that produce vehicle motion and to integrate those to estimate changes in speed and position. The sensing element is usually called an accelerometer. Integration is accomplished by electronics. To endow an inertial system with the ability to indicate position and speed of a vehicle accurately and reliably requires very considerable effort and ingenuity. Part of that effort must be directed to methods of stabilizing the gyro itself. With few exceptions, modern inertial systems are usually a part of an integrated system in which a radio navigation system provides periodic updates. The state of inertial development is such that no implementation can or should yet stand unaided for long periods.

Transit

The Transit system was mentioned earlier as an example of applying the Doppler effect in navigation. In simple terms, a navigator with a radio receiver acquires the signal from a satellite and measures the frequency shift caused by the satellite's high velocity. This must be a repetitive process so that changing frequency can be related to slant range changes to the satellite and the resulting data accumulated. By itself, the collection of range differences tells little. It is necessary for the navigator, his computer more precisely, to have the satellite's orbital positions when the Doppler measurements are made. It is also necessary to have approximately known position and motion for the receiver as well. The message transmitted by a satellite contains values for the parameters that define its orbit, so that its position relative to the receiver can be computed as the satellite makes its pass.

In contrast to other navigation systems, a position in latitude and longitude is determined for the navigator by use of one satellite and its signal. The drawback is that it takes between 10 and 16 minutes to determine a present position. During this interval, and to determine the navigator's position, his computer combines calculated satellite positions,

range difference measurements (counting Doppler cycles) and information regarding vessel motion.

Global Positioning System

The Global Positioning System combined some of the best known, basic principles and techniques of navigation with innovations to become a modern system that should meet most military and civil requirements for accurate position determination for a long time. For a navigator on Earth's surface, the circular line of position reappears in this system because distance measurements are made between receiver and orbiting satellites. Distance measurements to two satellites produce two circles that intersect, one intersection being at the navigator's position. As in the Transit system, each GPS satellite provides the navigation receiver with a message. In GPS, the message contains the data necessary to calculate the satellite's position, but also includes clock correction parameters and a parameter that permits an approximation to be made for atmospheric delay of the signal. It also contains a reduced accuracy 'almanac' containing similar information for all other satellites in the system.

For a receiver to operate successfully, it has to have an internal replica of the satellite's timing signal. It must also be able to compute the satellite's position using the data in the satellite message. As the satellite signal is received, the replica signal is shifted in phase to agree with the satellite signal. The phase shift is equivalent to a time interval, which equates simply to distance as described in connection with the Omega ranging process.

Each of the satellites contains an atomic clock carefully maintained in synchronization with a GPS system time, which is, in turn kept in step with the master clock at the U. S. Naval Observatory. As mentioned above, it is simply too expensive and logistically impossible to have such a synchronized clock in every receiver. Distances found by the above process, and the intersection of two position circles, would be inaccurate, at least to the extent that even a stable receiver clock is not quite accurate enough for the complete task. A third satellite distance is computed from measured phase shift. Again, the distance translates to a third line of position that does not generally intersect the first two lines at the same point. By repetitively adjusting the receiver clock by a constant amount (assuming a constant clock error) followed by recomputing each distance until the three lines of position all do intersect at one point, the correct, pinpoint position is determined.

The case of an aircraft in flight introduces a third dimension to the problem, its altitude above the Earth surface. Extension of the above operational description to this case is straightforward. Instead of measuring the distance to two satellites, the receiver must capture and measure signals from three, and compute their positions as well. For this case, the measured distances define radii of spheres, each sphere centered at a satellite. Theoretically, the common point of intersection for the three spheres determines altitude as well as latitude and longitude. But again, it is not to be expected that all of the spheres will intersect at a point, so a fourth satellite is used. As above, adjustments are made to the receiver clock until a pinpoint intersection is found. The number of active satellites in the GPS system is 24. For an aircraft and ships at least, there are always a sufficient number of available satellite signals to carry out the positioning process.

Since GPS broadcasts on two frequencies, the difficulty of propagation delay downward through the ionosphere is virtually eliminated by applying a formula that relates delay to the mathematical squares of the two frequencies. This technique was also used successfully by the Transit system. A tracking network and frequent uploads of orbit ephemerides also maintain available accuracy for the navigator. Use of a special coding in the navigation message (called pseudo random noise) combined with high frequency transmission enable the satellites to conserve power, and the user to access and process the signal reliably in the presence of considerable noise.

To some extent the high accuracy of the system can be a problem. Full accuracy has made necessary the compilation of a geodetic reference system that is commensurate, so that coordinates derived from GPS are correctly related to chart positions based on the same geodetic system. Not being aware of the situation, some navigators have placed exclusive, blind faith in a combination of GPS and charts based on a regional or an outdated geodetic datum, ultimately to find their vessel in peril or grounded.

Since the requisite messages for both GPS frequencies are not available to all, civil use accuracy does not match the full accuracy. Nevertheless, attainable accuracy using only the civil availability frequency is more than enough for the majority of users. On the other hand, with a special receiver that can reproduce and track the carrier frequency of the GPS signal, it is possible to obtain a precision of about 2

millimeters. While precision is not the same as accuracy, this tracking technique does have applications in surveying and geophysics.

An Eclectic History

Table 2 lists some dates that were particularly significant relative to transforming radio signals into simple lines of position and instantaneous indication of latitude and longitude. Also included, set apart, are four approximately dated periods during which significant research was being carried on that had direct impact on the ability to field modern systems. All modern systems that we have at present have been made possible by a combination of research, development and engineering in physics, radio circuitry and wave propagation, digital computer science, space science, materials science and microfabrication. Not revealed by Table 2 is the course of political events, particularly during the last 60 years, that had as much or more influence on the specific array of navigation now at our disposal. In what follows I briefly mention some particular events in the history of the few navigation systems I discussed above. That is not to say a very complete account would be misplaced or boring; rather, such a discussion is best left to the history of science.

Loran-C shares a name with Loran-A, but it is a different system. Work to improve Loran began in 1943 but, for a long time, the thrust of almost all research in radio was at higher and higher frequencies. There were problems with interference, bandwidth and propagation that had to be addressed. Utility of the low frequency, long wave part of the spectrum, once heavily used for long distance maritime communications, seemed to hold little interest. The final selection of the 90 – 110 kilohertz band for Loran-C resulted from the study and experimentation of relatively few people. Meanwhile, many experimental systems, with names largely forgotten, were tested and discarded.

As a direct benefit of three patents issued between 1974 and 1980, most Loran transmitters are now solid state, with the benefits of reliability and economy. Reliability is further enhanced by redundancy, and it is possible for stations to operate virtually unmanned.

Military requirements for Loran-C ended in 1994. However, at that time Loran-C could boast the highest number of users of any precise radio navigation system, and the number of users was continually growing. The system should remain viable for several years, even though many users will shift to GPS.

Table 2. Brief Chronology of Navigation Related Events

1837	– line of position by celestial navigation discovered
1887	– electromagnetic (radio) waves produced
1895	– transmission and reception of radio waves demonstrated
1896	– theory of the ionosphere proposed
1897	– electron discovered
1904	– first broadcast of radio time signals
1907	– triode vacuum tube announced
1922	– idea of hyperbolic radio navigation patented
1925	– height of ionosphere measured by pulse ranging
1937	– first hyperbolic navigation system (Gee) proposed
1942	– Gee system operational
1942	– Gyro system used to stabilize rockets
1943	– Standard Loran (later Loran-A) operational
1943-58	– research to improve Loran
1946	– first electronic digital computer
1947	– Radux system proposed
1947-66	– research on radio wave propagation, systems tested
1948	– invention of transistors
1951	– Ship Inertial Nav. System development initiated
1953	– highly stable crystal oscillator for radio frequencies
1955	– hybrid Radux-Omega system studied
1955-58	– stability of cesium beam frequency standards demonstrated
1956	– inertial navigation system installed aboard ship
1957-pres.	– space research
1957	– Doppler shift of Sputnik radio signals analyzed
1958	– Ship Inertial Navigation System deployed
1958	– Loran-C operational
1958	– Transit (Doppler) system approved
1962	– Radux abandoned, Omega system development pursued
1964	– Transit system operational
1970-pres.	– microelectronic development
1971	– Omega system operational
1972	– pseudorandom noise code ranging signal demonstrated
1973	– GPS development initiated
1993	– GPS fully deployed (24 satellites)
1996	– Transit updates discontinued
1997	– Omega transmitters turned off

The major problem with current inertial navigation is the tendency for existing systems to accumulate errors fairly rapidly and pass those on as erroneous indications of position and speed. Consequently, periodic position input is required to reset or update the inertial system. Updated position input must be obtained from other systems, and the frequency with which that is required equates to more or less autonomy for the navigator and his vehicle.

Inertial navigation is only one of several uses for inertial systems, and research to create better inertial systems has some interesting aspects. To a large extent, focus has been away from spinning wheels and their mountings and toward use of other physical principles and dependence on computers. New devices, some having no gyros or gimbals are still referred to as gyros. They are also known by esoteric names such as electrostatically supported, hemispherical resonator, ring laser and interferometric fiber optic gyros. The last named two are optical gyros, based on a general relativistic effect. Impetus is another aspect. Navigation being but one application of inertial devices, many improvements and innovations appear to be driven at present more by demand for smaller size, less weight and cost to own, and less by a quest for greater accuracy and reliability. It may be a long time until an inertial, or other self-contained system, fulfills all navigation criteria or competes with radio based systems.

The U. S. Navy originally developed Transit to update the inertial navigation system aboard Polaris submarines. Transit began operation in January 1964 and, because of the accuracy it afforded in determining position, it has been credited with giving birth to the science of satellite geodesy.

Transit satellites were exceptionally reliable and, when the last satellites were placed in operation, the system reached peak capability and had about 100,000 users. Operation of the system has been discontinued in favor of the Global Positioning System, but the Russian Cicada system, also operating on the Doppler principle, continues.

Except for a few requirements, the Global Positioning System offers all the performance and accuracy that the military needs. To everyone else, it appears to be the best of all systems. In fact, it is now evolved to the position of creating its own requirements in the commercial arena.

GPS was almost cancelled at one point and was degraded at another. A joint program for development of GPS (also called NAVSTAR then and at times since) came before the Defense System Acquisition Review

Council (DSARC) in 1973. The program, as presented, was essentially an Air Force system having some undesirable aspects. The review failed but, fortunately, strong support was expressed for a broadened system concept that would represent the views and requirements of all services. Work then began on synthesis of the best of all extant concepts for a system.

In 1979 another DSARC review gave approval for continued development of the system with its 24 satellites as planned. However, at a higher level review, at which money was the sole unit of measurement, it was decided to reduce the GPS constellation to 18 satellites. This triggered studies for the purpose of redesigning the orbit plane configurations for the administratively revised system. What seemed the best alternatives would, it appeared to me, demand perfect reliability of orbit insertion and operation for all 18 satellites. Further, there would be some locations on the Earth for which the geometry of available satellites would at times be unfavorable, particularly for aircraft. Fortunately, the 24 satellite constellation was reinstated.

The Cardinal Principle

To this point, I have described a few navigation systems particularly as they illustrate the use of some basic principles. There is one principle, neither geometric nor physical, as old as navigation beyond familiar landmarks and still applicable to modern navigation. The principle itself is simple but cardinal: A navigator should use every available means to determine his position.

A navigator who must steadily rely on an inertial system adheres to the principle whenever he updates, or resets, the inertial system by using an external source. Of course modern navigation is heavily reliant on electronics, and electronics is readily adaptable to combining two or more navigation system signals in various ways to provide an optimum result. In fact, this has been done many times. A simple, obviously obsolete example is the combination of Omega and Transit. Omega as a global system could provide a position almost continuously (every 10 seconds), with successive positions enabling a calculation of estimated speed. Transit provided a more accurate position, but on an irregular basis. Transit also required an estimate of position and speed as input to its data processing. By combining the two systems electronically, at the receiver, Omega could be considered the primary system, with accurate Transit positions used to minimize the errors in Omega. In this context the system becomes a global Differential Omega system. Complementary systems,

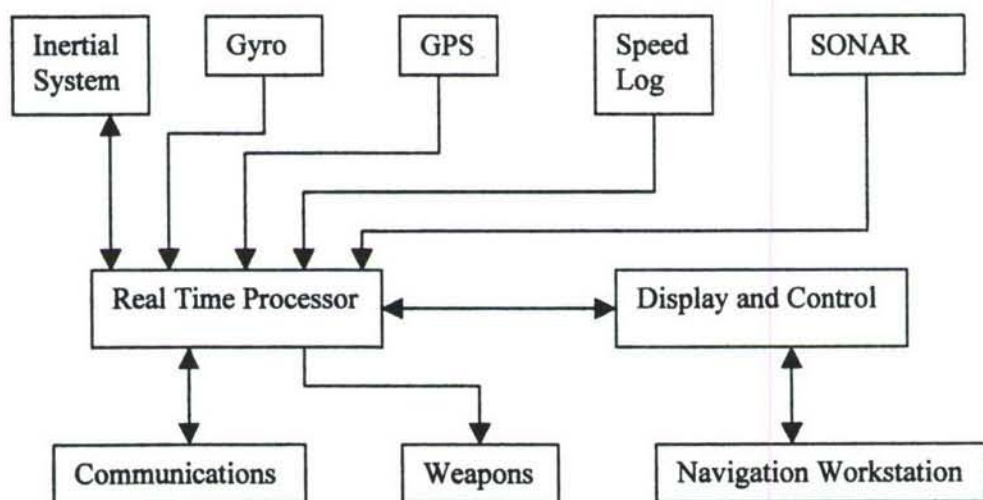


Figure 5. Elementary integrated navigation system

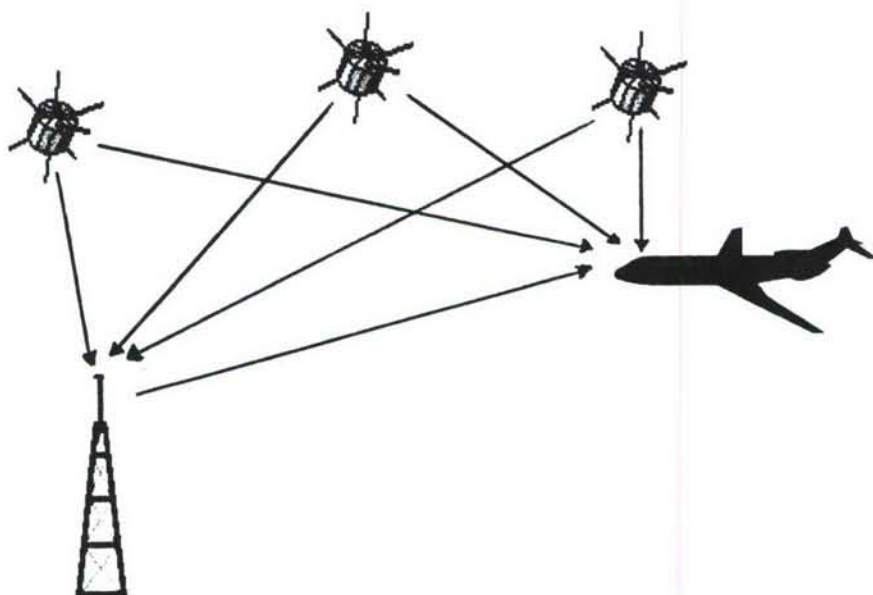


Figure 6. Differential (GPS) navigation.

such as described and whether proposed or built, have been variously called composite, hybrid, and integrated.

The GPS is continuously available worldwide, so that it is natural to ask whether it is any longer worthwhile to consider integration with another system. A positive answer is derived from considering issues of vulnerability and of operations in locations where GPS signals are blocked by natural or artificial objects. Taking the issues into account, the U. S. Navy, for one, has been developing massively integrated systems for use aboard ships. These systems are complex and evolving. However, Figure 5 is a block diagram of an elementary system that illustrates how integration could proceed for a combat vessel. Note that all navigation signals are directed to the real time processor, which quickly combines the inputs according to their relative accuracy and reliability. Also note that the processor provides updates to the inertial system. The "Gyro" block refers to the gyrocompass, which displays direction only. The navigator can adjust or override the processor using the display and control unit.

Aside from the benefits of integration, there is a situation that calls for a different solution. From the beginning of GPS development, it was intended that its highest accuracy capability would be withheld from all but authorized users. For GPS civil use, especially on or over vast stretches of terrain, the restriction is of little consequence. There are however, areas of operation by aircraft and ships in which highest accuracy is needed. It can be obtained by an investment in a differential system. The idea is conceptually simple and illustrated by Figure 6. A GPS receiver is monitored at an accurately known position. Any positions determined at the receiver that show differences from the known position are considered the result of errors in the system; in particular, signals that don't provide full system accuracy. It is also considered that those deviations from the known position are exactly the same anywhere in the vicinity of the known position. A transmitter at the accurately known location proceeds to broadcast a message quantitatively informing all GPS users in the vicinity what the deviations are. GPS users, on receiving that message, then have the opportunity to apply the deviations as corrections to positions determined directly from the GPS satellites. This Differential GPS concept has been extensively tested, automated, and found very successful.

A Last Word

The preceding paragraphs illustrate that absolute navigation is concerned primarily with determining present position and is based on straightforward geometric and physical principles. Also, from the history outlined by Table 2, it is seen that modern systems had to await developments in science and technology in order to be built and to overcome, or compensate for, additional physical and geometric effects. As a result, the equipment that constitutes a modern system is not only highly complex, but any such system requires an extensive, supporting infrastructure also. Complexity and extensive infrastructure render modern systems vulnerable, and something must be said about alternatives.

There are numerous possibilities for complex, high-tech systems to fail or become unavailable. Any practicing navigator with experience knows the value of having alternative methods of navigation at hand. At least one alternative must be independent of primary systems; it would be best if it has no point in common with a primary system such that failure at a common point eliminates both alternatives. The most obvious example of a common point failure is an electronic suite or integrated system in which all component devices depend on a single electric power source. The example is easily understood by considering Figure 5. Additional examples could be cited.

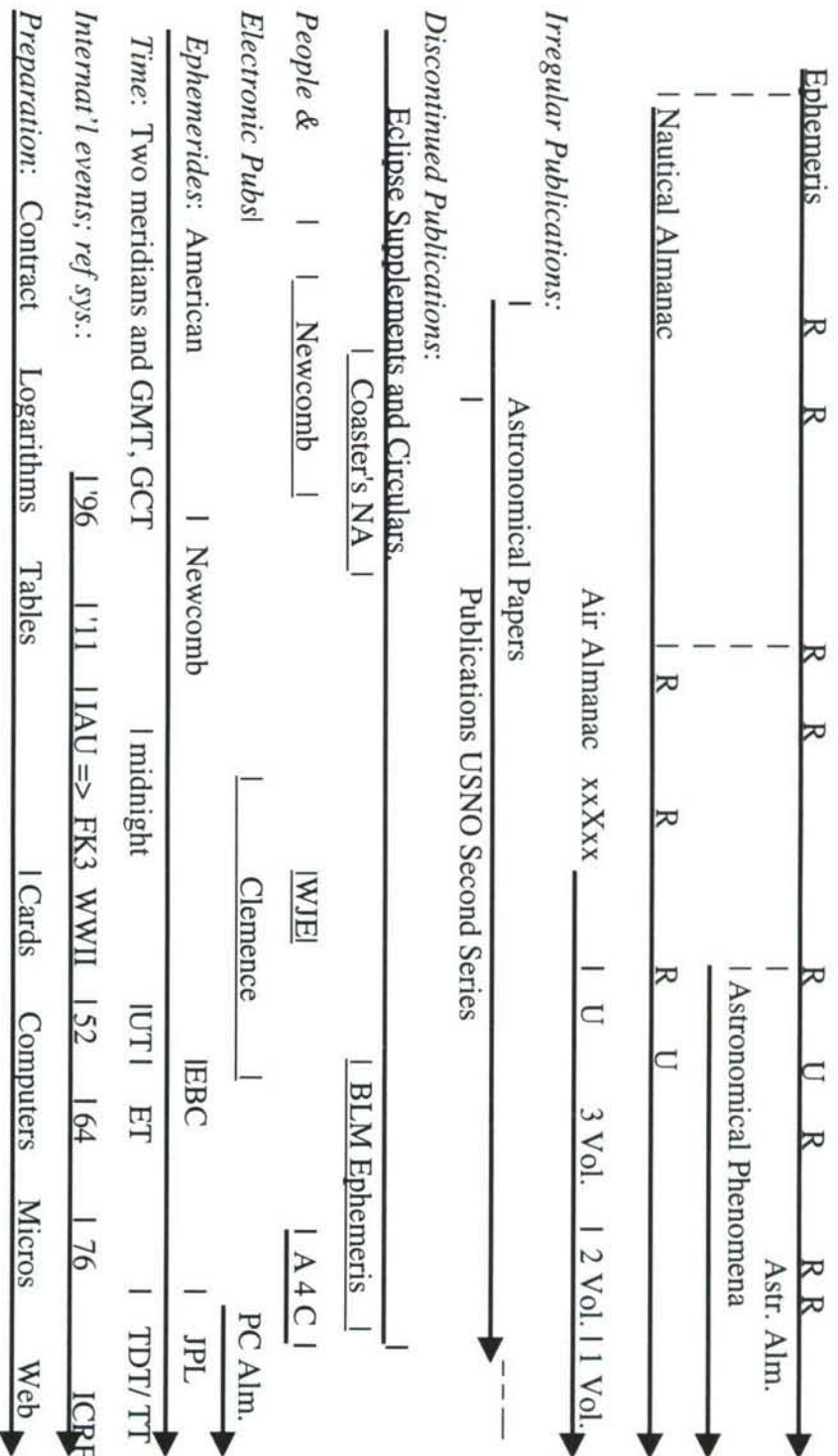
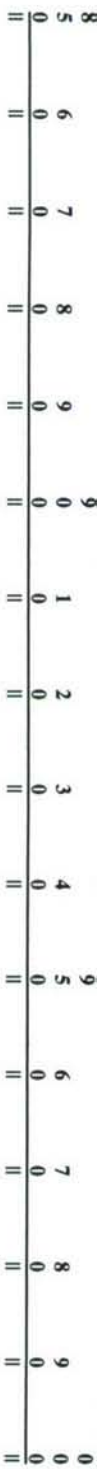
Until Loran-C became widely available, celestial was the standard of excellence for determining position in deep water. Celestial navigation is both an alternative and modern in the sense that it is still available in classic form and procedures when other systems cannot be used. Precisely because of its classic procedures, it lately stands as a weak backup to electronic systems. With the exception of the rigorous and flexible computer program STELLA (System To Estimate Latitude and Longitude Astronomically), there has been no attempt to automate the process of celestial aboard ship. Further, the extension of celestial capability to 24-hour capability has not gone beyond successful demonstrations of feasibility. In contrast, there are many applications of modern technology to at least some elements of celestial navigation in the form of automatic star trackers for missiles, spacecraft and long-range aircraft. I believe that an attempt to automate the total process of celestial for surface vessels is possible and reasonable, certainly to proceed along lines that maintain independence from a primary or other alternative system. For instance, power consumption by an automated celestial system ought to be minimal

so that battery operation is a consideration. Other symposium participants address this subject more fully.

Acknowledgements

I am indebted to Dr. George H. Kaplan for providing some critical details and discussions, and for reading an early version of the manuscript. Since I was, for a time, editor of the journal *Navigation*, and was engaged in the production of navigational almanacs for a longer time, some of the preceding material is from personal knowledge of the subject. For many quantitative and historical details, I have also relied on a few references that should be mentioned.

1. Except for too much emphasis on radio direction finding, S. F. Appleyard, *Marine Electronic Navigation* (Routledge & Kegan Paul, London, Boston and Henley, 1980) contains very readable discussions of basic principles and the operations of some modern navigation systems. Figure 2 in this paper was adapted from that book.
2. Unsurpassed for first-hand accounts of the development of modern systems (to 1995) are two anniversary issues of *Navigation*: Vol. 18, No.1, 1971 and Vol. 42, No.1, 1995 (Alexandria Va.: The Institute of Navigation).
3. The standard reference for an introduction to the engineering aspects of GPS is *Global Positioning System*, Vol. I (The Institute of Navigation, 1980). Advanced concepts and applications are found in succeeding volumes in the series.
4. The many aspects of applied marine navigation (to 1977) are fully explored in two volumes of the *American Practical Navigator* (Washington: The Defense Mapping Agency, Pub. No. 9, 1977).
5. An extensively revised edition of *The American Practical Navigator*, containing much new material, was published in 1995. The National Imagery and Mapping Agency is currently responsible for this standard reference.



Abbreviations:
R = Revision
U = Unification
X = Experimental

WJE = Wallace J. Eckert
EBC = Eckert-Brouwer-Clemence Integration and Brown's Lunar Theory
A 4 C = Almanac For Computers
PC Alm. = Floppy Almanacs, MICA, STELLA, etc.

Figure 1. Timelines for Publications, People, and Major Influences

EVOLUTION OF THE PRODUCTS OF THE NAUTICAL ALMANAC OFFICE

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Introduction

My career of nearly 37 years has been spent almost entirely in the Nautical Almanac Office, and I now head the small division that still proudly bears the name. The invitation to review the products that the office has produced gave me the opportunity to step back from the details and look at a broad perspective. Rather than define the history in terms of the products, I'd like to look at some parallel factors in astronomy and navigation, their interaction with the Nautical Almanac Office, and the products that resulted.

Most of you are familiar with either *The Astronomical Almanac* or the navigational almanacs. The first product of the office, *The American Ephemeris and Nautical Almanac for 1855*, superficially bears little resemblance to *The Astronomical Almanac for 2000*, its direct descendant published last month. That first edition was the only product of the office, whereas *The Astronomical Almanac* is just one of several products. The concept of a product, especially within a mission-oriented institution, also means there has to be a demand or requirement for it.

Figure 1 displays the parallel timelines and significant milestones. The lines in the top part show the evolution of annual printed products. The middle part shows some important people and electronic products. The bottom part shows some of the trends and requirements driving the evolution of the products. This paper will describe the relationships among them.¹

National Almanac Offices

"Almanac" and "ephemeris" have imprecise definitions. "Almanac" derives from the concept of calendar and almanacs have existed for centuries. It now commonly refers to similar information in an annual publication. The earliest almanacs often had two components, a calendrical one for listing dates and festivals, and an astronomical one for configurations of the Sun, Moon, planets, stars, phases of the Moon, weather predictions, and other such

“useful” information. “Ephemeris” derives from the Greek for something lasting a very short time. The current usage is in the sense of tabular representations of the positions of celestial bodies as a function of time. The distinction between an almanac and an ephemeris is therefore somewhat blurred.²

In the 15th century, great voyages of exploration and discovery out of the sight of land made the determination of longitude a problem of paramount importance. Many methods were proposed, but few were practical. The most notable schemes required observations of events that could be observed simultaneously from many locations: solar and lunar eclipses, occultations of stars, and the eclipses of the satellites of Jupiter. The drawback was that these events occurred at wide intervals, rarely at times convenient to a navigator, and were difficult to observe because of inadequate instruments and the motion of a ship. The method known as lunar distances was the most attempted, but rarely successful because the lunar theory was so inaccurate.³

National offices were intended to assure that accurate information was reliably available to navigators for that country. In France, a private almanac called *Connaissance des Temps* was taken under the auspices of the French Academy beginning in 1679. That publication provided the earliest explanations of finding longitude using the Moon. The British Nautical Almanac Office was established with the main purpose of providing the information for the application of the method. The first issue appeared in 1767. The time was right, as Tobias Mayer had just completed a new, more accurate, theory of the Moon. Germany and Spain soon established their own similar offices and publications.⁴

The United States Nautical Almanac Office

There were, inescapably, political considerations behind the founding of the American Nautical Almanac Office and its development.⁵

The young United States of America used the British Nautical Almanac for navigation and surveying, as well as astronomical purposes. As the country grew geographically and also became a maritime power, there was increasing need felt for a national almanac. Even before establishment of a national observatory in 1842 there was talk in the astronomical community of a federally supported national almanac. In 1844, John Y. Mason, Secretary of the Navy, noted our dependence on foreign nations. There was a dilemma, however. Matthew Fontaine Maury, the Superintendent of the new national observatory, was of the opinion that an

American almanac should be wholly American in both calculation and observations. There was fear that such a product might be so inaccurate as to be dangerous. On the other hand, if the product merely duplicated the British work, why expend the funds? There was also a division between those who thought a national almanac should be solely for navigational purposes, and those who wanted to do a service to astronomy in general.⁶

At last, on Saturday, 3 March 1849, the last day of the administration of James K. Polk, an appropriations bill passed by Congress for the Naval Service provided

...That a competent officer of the navy, not below the grade of lieutenant, be charged with the duty of preparing the Nautical Almanac for publication, and that the Secretary of the Navy may, when in his opinion, the interests of navigation would be promoted thereby, cause any nautical works that may, from time to time, be published by the hydrographical office, to be sold at cost,...⁷

Despite the wording, this authorization was not construed as placing the almanac under the hydrographical office. A Nautical Almanac Office was established at the beginning of the next fiscal year, 1 July 1849. Separate from the national observatory, it was located in Cambridge, Massachusetts, next to the Harvard College Observatory, the best research observatory in the United States. Benjamin Peirce was there, and served as *de facto* scientific director. The first Superintendent of the Nautical Almanac Office was Navy LT Charles Henry Davis. He had experience with navigation, but also strong ties to the scientific community. He was a protégé of Peirce.⁸ Davis' view was that the almanac should serve for both navigation and astronomy. In navigation, it would make the United States independent of Britain, and in science it would be more perfect than any existing almanac.

Production of the American almanacs was, for at least the first century, considered to be extremely important for the government and for astronomy. Eventually the missions of the Nautical Almanac Office and the Naval Observatory intertwined. The Nautical Almanac Office was moved to Washington in 1866, and then located on the new grounds of the Observatory in 1893. Administratively, it was separate until sometime between 1897 and 1907, when it was taken under Observatory administration.⁹

When CAPT W. J. Barnette assumed the duties of Superintendent of the Naval Observatory in December 1907, wishing to have more information on the workings of the department of Astronomical Observations, he appointed a board to evaluate staff suggestions on the plan and scope of work. The board worked from May to July 1908, and its recommendations

were issued as an instruction by Thomas Newberry, Secretary of the Navy, in March 1909:¹⁰

There is hereby formed an astronomical council composed of the following members: The Superintendent (ex officio), the Assistant Superintendent, such assistants in charge of the astronomical divisions as the Superintendent may designate, and the Director of the Nautical Almanac.

The council should be guided by the fact that the most important astronomical duty of the Government is the publication of a nautical almanac, and as that is intended not only for the use of navigators, but also of astronomers in the most delicate investigations known to their science, it should be kept up to the highest attainable pitch of accuracy. To that end, continuous fundamental meridian observations upon the Sun, Moon, planets, and stars are absolutely necessary and constitute the astronomical essentials.

The astronomical work of the Naval Observatory shall be so planned and executed as best to subserve the following purposes, and no others, to wit:

To furnish to the Nautical Almanac Office, as far as may be possible, such observations and such data as may be needed for carrying out the purpose of the law under which the appropriations for that office are made from year to year, which is as follows:

For * * * [sic] preparing for publication the American Ephemeris and Nautical Almanac and improving the tables of the planets, moon, and stars * * *.

The principal work of the observatory shall be in the field of the astronomy of position as distinguished from astrophysical work, and shall be the continued maintenance of observations for absolute positions of the fundamental stars and of stars which are to be made fundamental, and in addition the independent determination by observations of the Sun, of the position of the ecliptic, and of the equator among the stars, and of the positions of the stars, Moon, and planets with reference to the equator and equinoxes.

Creating and Managing an Almanac.

In starting up a new product, Davis was faced with basic questions that are still valid today: What is its application, what information should it offer, how should information be presented, how should it be calculated and by whom, what medium should be used, how should the product be

produced, how should it be distributed, and so forth.

Management of change after creating a product is a policy decision. As Eckert¹¹ reports, many suggestions on change are received by an almanac office. A decision on which improvements to adopt and when to adopt them is difficult and can be made only on the basis of all the factors involved, and in accordance with a consistent long-range policy. The almanacs cannot be used lightly for experimentation or to reflect personal whims. Each modification must be examined not only for intrinsic worth, but also for consistency with the almanac as it exists or is planned for the future. The saving brought about by an alteration must more than offset the inconvenience caused by the change. There is a history in the office of consulting outside experts for advice, or for comments on proposed changes, both in existing products or new ones.

There is an inherent time lag in making changes. From the establishment of the office, a goal was to have the navigational information available for use three years in advance, to supply ships going on the longest voyages. This means that preparation must begin even earlier, the amount depending on the methods. Consequently, this defines the time lag between making a decision and seeing the result appear in the finished product.

In the first edition, as mentioned earlier, for navigational purposes the almanac had to provide at minimum sidereal time for the Greenwich Meridian, lunar distances, and ephemerides of the Sun, Moon, and planets. For astronomical purposes and surveying, and observations for improvements of the theories, it contained transit ephemerides of the Sun, Moon, planets, and many stars for Washington. Occultations of stars by the Moon and eclipses of the Sun provided important opportunities for checking the accuracy of the ephemerides. This was the basic content for several years.

Examples of the most important changes in the navigational portion and their justification are as follows. Ephemerides of more planets were introduced in 1882 as part of a group of changes suggested by Newcomb and approved by the National Academy of Sciences.¹² As altitude-intercept methods were introduced, the method of lunar distances fell into disuse. That portion of the almanac was removed in 1912 after an investigation conducted by the Chief of the Bureau of Equipment in 1907 showed it was little used.¹³ When the navigation portion changed from a reprint into a separate publication for navigators in 1916, tabular data were given hourly instead of daily. Rising and setting phenomena of the Sun and Moon first appeared in 1919. From 1929 content and arrangement was influenced by the needs of aerial navigators, as we shall see later. In 1934 the Greenwich Hour Angle

of Sun, Moon, and stars was included solely for navigators. Page layout for air navigation influenced the layout for surface navigation.

Examples of changes in the part for astronomy and geography include the following. Davis wanted to include full ephemerides of all minor planets, but as the number grew rapidly, this was impracticable. A century later, a selected few were included for special projects. As more satellites of planets were discovered, better dynamical ephemerides were included. Physical ephemerides of planets and the Moon were added. Longer lists of star positions were always in demand, such that a separate publication was created for them. Pluto was added in 1950, minor planets 1-4 in 1952 for use in studies of the equinox, the ephemeris for the Washington meridian was removed, and so forth. We will not delve deeper into details.

International Cooperation

Let us consider the timeline of Figure 1 for international meetings and other influences.

Today, the American and British Nautical Almanac Offices strive to comply with recommendations of the International Astronomical Union (IAU). There were efforts at some international coordination, if not cooperation, from the beginnings of the American office. Davis, wanting to publish ephemerides of all the minor planets, suggested to the European almanac offices a joint program. They never responded, but the idea was impractical anyway as the number grew rapidly. In 1896 a meeting of directors of national ephemerides was called in Paris. The matter of common planetary ephemerides was somewhat delicate because all the European offices used the work of Leverrier, which in Simon Newcomb's opinion did not incorporate enough observational data.¹⁴ There were some agreements made on which constants to use for the fundamental reference system. They were incorporated into the almanacs for 1901. Newcomb continued to introduce his own theories into the American almanacs.

The next international conference was called in 1911, again in Paris. Although the Conference was primarily concerned with obtaining a greatly increased list of apparent places of stars, it extended its attention to all the ephemerides of bodies in the solar system. The most significant of its comprehensive recommendations was to reduce redundant calculation by distribution of calculations among the five principal ephemeris offices (France, Germany, Great Britain, Spain, United States). It also specified standards of calculation and presentation, arranged for publication of additional data, and fixed the values of some constants to be used in the

ephemerides.

Official approval was in some cases necessary for the adoption of these recommendations. The resolutions were distributed to American astronomers, and 84 responded, generally favorably. The naval appropriations act passed by Congress on August 12, 1912 had three provisions that influenced the American almanacs. The one of interest for international cooperation authorized exchange of data with foreign almanac offices. The Nautical Almanac Office expressed willingness to adopt the program of exchanges of data recommended by the Congress, with understanding that it could be terminated upon one year's notice, and with the conditions that it was not committed to printing extra decimals of precision in the ephemerides of stars, nor to cease publishing ephemerides for the meridian of Washington. The changes accepted were introduced into the volume for 1916, at the time that *The Nautical Almanac* became a separately prepared publication.

In 1919 the IAU was established. Commission 4 on Ephemerides provided the formal contacts by which the previous agreements could be continued and extended. The agreements made in 1911 had been directed to reduction of the total amount of work by avoiding duplicate calculation. In 1938 Commission 4 recommended that the principle should be extended to the avoidance of duplicate publication. As a first step the apparent places of stars then printed in all the principle ephemerides would be collected into a single volume. This was implemented in 1941 by the publication of the *Apparent Places of Fundamental Stars*. That material was removed from the national almanacs, relieving the office of some burden of calculation.

After the disruption of World War II, the Director of the Paris Observatory convened a conference in Paris in March 1950 to discuss the fundamental constants of astronomy. The most far-reaching consequence was in the recommendation that defined ephemeris time and brought the lunar ephemeris into accord with the solar ephemeris. These recommendations were adopted in 1952 and implemented in the almanacs for 1960.

In 1963 at IAU Symposium 21 in Paris, it was concluded that a change in the conventional IAU system of constants could no longer be avoided. At the Twelfth General Assembly in 1964 a list of constants proposed by a working group was adopted and recommended for use at the earliest practicable date in the national and international astronomical ephemerides. This was done in the almanacs for 1968. Further study by IAU groups led to recommendations for far more substantive changes in the constants, reference system, and ephemerides. The recommendations were

adopted in 1976 and fully implemented in the volumes for 1984. The volumes for 1981 were united under a single title, and the format was changed.

The selection of a standard reference system for stars was always an important topic at these international conferences. Newcomb was pleased with the work of Arthur Auwers at Berlin, but noted a systematic difference in the right ascensions from the stars used in the *American Ephemeris*. Therefore he decided to construct his own catalogue for right ascensions, while adopting the work of Lewis Boss for declinations.

In 1938, the German office finished the FK3, about the same time that the U.S. Naval Observatory finished its zodiacal catalogue. The latter was not printed for lack of funds, and in 1941 the FK3 was adopted as an international standard.¹⁵

Source of Theory

It is frequently supposed, even these days, that our ephemerides are the direct result of a set of formulas evaluated as functions of time. In fact, they are the concluding step in a sequence of three distinct processes. The first is construction of a theory, defining the problem in mathematical terms and solving the equations of motion. This includes comparison to observations for refinement. The second is construction of an intermediate device that reduces the evaluation of a theory to a series of arithmetic operations. Until mid-20th century, that was a set of tables. Nowadays it is most often the output of a numerical integration. The third is extraction of the data, conversion of coordinates, and arrangement of numerical results.¹⁶

There have been few major changes in the basic ephemerides of the almanacs, but they occurred more frequently over time. By directing the attention of American astronomers to the need for improved theories of the lunar and planetary motions, the *American Ephemeris* became an important factor in the contributions to celestial mechanics and astrometry made in America.¹⁷

At the founding of the office, the theories and tables employed at the several national almanac offices were a patchwork collection, with additions, corrections, and adjustments which enabled predictive accuracy for only a few years in advance. They were based on only 50 years of accurate observations. Davis had to use the best and most recent theories, while starting work to produce new ones. Even before the first volume was begun, special new theories and tables were worked out for several bodies. As a test,

predictions for the solar eclipse of 28 July 1851 were prepared from the American, British, French, and German ephemerides and compared to observed timings. Davis was obviously proud to report that the American calculations were far superior to the others in accuracy. The British almanac was the furthest off, with an error up to 85 seconds of time, corresponding to an error in longitude of 15-20 miles.

Davis laid out a plan for development of new tables, and his successors kept it up. However, Davis and Winlock both noted in their annual reports, in a theme that continues to this day:¹⁸

While the importance of such investigations are admitted in the work of the office, they are subordinate to the current duties necessary for the preparation of the annual volume, and the almanac must be indebted to the devotion of the astronomers to their science for the voluntary contribution of much time and labor to the class of subjects here referred to; the gentlemen engaged upon these are also actively employed on the current duties of the office.

Simon Newcomb was appointed Superintendent in 1877, and in his first annual report, he states "The most urgent want of the office at the present time is a set of tables of the Moon and planets, corresponding in accuracy to the present state of practical astronomy, and founded on entirely homogeneous data."¹⁹

He began a program to determine fundamental astronomical constants from all available observational data, and to discuss all the observations of the Sun and planets made worldwide since 1750. From this, he and G. W. Hill constructed new planetary theories and tables, and a catalogue of 1,596 fundamental stars. Through the Secretary of the Navy, in December 1877 Newcomb submitted a proposal of fifteen suggested changes in the astronomical ephemeris to the astronomers of the country that were referred to a committee of the National Academy of Sciences. Most were sustained, some modified, and they were incorporated into the volume for 1882. After the international conference in 1896, his new theories were introduced into the American and other almanacs starting with 1901. At the time, he predicted that they would only be good for 70-100 years.

Another provision of the Act of Congress in 1912, referred to earlier, authorized personnel to conduct this research if time permitted.

Starting in 1938, extensive discussions of accumulated observations of the Sun and planets indicated appreciable discordances. Gerald Clemence, Director of the Nautical Almanac Office, reported that the various defects and inadequacies indicated that a new attack on the whole problem of the

motions of the principal planets was needed. The accumulation of observations since Newcomb's time was massive, and extensive theoretical and computational work was needed to utilize it and to improve the form of the theory.²⁰ In 1947-50, Wallace Eckert, former director of the NAO, Dirk Brouwer of Yale, and Gerald Clemence, then current director of the NAO, undertook to reconstruct all the planetary theories, based on still more observations, using computers to do a numerical integration for comparison. The principal result was a numerical integration of the outer planets that covered the span 1653-2060. In 1952-54, Brown's lunar theory was evaluated from theory rather than the tables. The results were incorporated into the almanacs starting with 1960.

After the war, more observations flowed in, including the new dimension of distance and using non-optical detectors. Driven by requirements of the space age, the Jet Propulsion Laboratory (JPL) developed extensive new theories of planets and satellites, based on but not completely conforming to IAU guidelines adopted in 1976. Their development and lunar ephemerides DE200/LE200 were taken as the basis of the almanacs starting with 1984.

In 1994 the IAU adopted a new International Celestial Reference System (ICRS). JPL has a new Development Ephemeris that conforms to the ICRS, and we contemplate introducing it into our almanacs for 2002 or 2003.

Time and the Almanacs

Davis stirred up another controversy when he was planning the first issue of the *American Ephemeris*. He asked what meridian to use — Greenwich, or one in North America? It had not been specified in the Act that authorized the office. To use the Greenwich meridian would be to redo the British Almanac, and surely an American product was wanted.²¹ The question was taken to the American Association for the Advancement of Science and referred to a committee of eminent astronomers and mathematicians. In February 1850 the House Naval Affairs Committee took up the issue. On 2 May it proposed a joint resolution that was adopted in an appropriations bill on 23 September:

that hereafter the meridian of the Observatory of Washington shall be adopted and be used as the American meridian for astronomical and geographical purposes, and such part of the computations of the Nautical Almanac as may be designed for the exclusive use of navigators, shall be adapted to the meridian of Greenwich.²²

This was a compromise, but also recognition by the Congress that the Almanac was not only for navigators, but also astronomers and geographers. The division of material into parts for navigation and astronomy permitted a reprinting of the first part separately, which commenced in 1858. The provision for two meridians was repealed by the previously mentioned Act of Congress of August 12, 1912. Nonetheless, despite international pressure to use the Greenwich meridian, two meridians were used in *The Nautical Almanac* until 1934 and the *American Ephemeris* until 1950.

Until 1925 there was continued international effort to standardize on the use of a common term for the time argument of the ephemerides. The astronomers wanted to use Greenwich Mean Time with the day starting at noon, but some places still used Greenwich Civil Time with the day starting at midnight, and there was confusion over whether the day started at midnight or noon. In 1925 everyone agreed that the day would start at midnight. In the volumes for 1939-1952 time is listed as both Greenwich Civil Time and Universal Time. In 1953, the term Greenwich Civil Time was discontinued. The term Universal Time was adopted for astronomical use, while the term Greenwich Mean Time was adopted for navigational use. The latter was converted to Universal Time over 1985-1990. Meanwhile, in 1950, Clemence proposed the introduction of Ephemeris Time as the independent argument, separate from Universal Time. This was adopted in 1952 and implemented in 1960 with the Ecker-Brouwer-Clemence integrations. That was superseded in 1984 by the introduction of Dynamical Time with the JPL ephemerides, and that concept is still being refined.

Presenting the Data: Calculation, Typesetting, and Proofreading.

We mentioned earlier that there are three distinct steps in preparing an ephemeris for presentation. Clemence wisely observed that there is also a fourth: keeping out mistakes.²³

During its earliest years, the NAO had no permanent staff beyond the Superintendent and a few clerks and proofreaders. The superintendent contracted with various astronomers and mathematicians throughout the country for the computations. Some of the most eminent American astronomers of the time took part in this work, and without their cooperation it is doubtful whether the project could have been successfully accomplished. Davis felt that it also created general interest in the character and prosperity of the work. Newcomb, early in his tenure as Superintendent, noted that two-thirds of the ephemeris calculations were done by piecework. This took extra lead time in the preparation of copy. He thought it would be more efficient

to have the planetary work done by one expert. Newcomb also noted in an early annual report that typographical and other errors in the published *American Ephemeris* were frequently reported. Knowing that he had to maintain trust in the integrity of the publications, he put proofreading under the supervision of a single responsible assistant, Mr. D. P. Todd. Only in 1950 was the use of pieceworkers outside the office entirely discontinued.

The naval appropriations act passed by Congress on August 12, 1912, provided

That any employee of the Nautical Almanac Office who may be authorized in any annual appropriation bill and whose services in whole or in part can be spared from the duty of preparing for publication the annual volumes of the *American Ephemeris* and *Nautical Almanac* may be employed by said office in the duty of improving the tables of the planets, moon, and stars, to be used in preparing for publication the annual volumes of the office.

It was a continuing thread of comment throughout the annual reports that it was difficult to find competently trained staff, and even more difficult to hire them when the authorized pay was so low — lower than that of a common clerk. The annual report for 1938 laments the loss by retirement or death of experienced astronomers all over the world, and adds:²⁴

At the last three meetings of the IAU, decisions were made over the protest of experienced astronomers, and then had to be reversed at the next meeting. Many observatories have ceased fundamental astronomical work, as the younger generation seeks something more attractive, less monotonous, and less arduous. Maintaining staff for fundamental work is expensive.

Astronomers welcomed any development that promised to relieve the amount of calculational labor and increase the reliability of the results. L. J. Comrie, Director of the British Nautical Almanac Office, started working with calculating printers as early as 1929, and Wallace J. Eckert was working with punched card equipment by 1933. He was brought in as Director of the American Nautical Almanac Office in 1940, to introduce punched card equipment and apply it to the production of the newly created *Air Almanac*. The machines helped compensate for a wartime shortage of staff. Machines calculated the data and generated tables; the tables were photo reproduced and also proofread by machine methods. The resulting almanac was the most reliable and accurate yet produced. By the time war urgency passed, there was a commitment to continue using tabular equipment to produce the

almanacs. Starting in 1945, a specially built card-operated typewriter was producing camera copy for *The Air Almanac*, a method later applied to *The American Nautical Almanac* and other publications. Introduction of the same equipment into the British office in the 1950s enabled unification of the British and American Nautical Almanacs from 1958. The Air Almanacs had already been unified in 1953. Similarly, the Ephemerides were unified in 1960, with each office preparing half the publication. We are now working with HMNAO to make it look like a uniform product.

Programmable computers were installed and utilized from the late 1950s onward, and used for both calculation and typesetting. In the mid-60s, the Government Printing Office began using typesetting equipment driven by computer-generated tapes, and went through several generations until the late 80's. Though they were generally more accurate than the old conventional methods of setting cold type, they weren't always any faster or easier! Right up until 1995-1996, preparing copy for an annual volume for reproduction and printing might be spread out over several years. Now, all the camera copy is produced right in our office and delivered to the printer ready to reproduce. Unfortunately, overconfidence in the reliability of computers without considering the human factors had led to some embarrassing errors and oversights, and we are paying particular attention to proofreading and examination again.

Distribution

The mainline printed products of the office produced as directed by law and through congressional appropriations have not generally been aggressively marketed in the United States. As a result, there was no incentive to make changes to appeal to a wider audience. For the first 60 years or so, the office itself handled sales, either directly or through designated agents. The Bureau of Equipment handled distribution to the Navy and other military components. Around 1908-1910, public sales were turned over to the Government Printing Office, but distribution to the Navy, military units, and exchange libraries came back to the office. In 1980, an agreement was reached with the Defense Mapping Agency to have them do distribution for the Department of Defense, and this has been passed on to the Defense Logistics Agency as of last year.

The office has distributed data in camera copy since the 1940's, and in machine readable forms for special purposes ever since computers were introduced. Participation in international exchanges tended to discourage changes. Since about 1986, we have been exploring the use of computer

disks, the Internet, and the World Wide Web for distribution of not only products, but also services.²⁵

Special Considerations for Navigational Almanacs

The Nautical Almanac was a reprint of the nautical portion of *The Astronomical Ephemeris and Nautical Almanac* from 1855 to 1915. In 1916, because the speed of ships had increased enough that the process of taking sights had to be expedited, the presentation of the data was completely redesigned. The original book had to be opened to too many different places to collect all the information required. The new arrangement reduced the number of openings required, and with accuracy only to the number of places required.

Development of an air almanac began in the late 1920's. As aircraft began making long flights, it was discovered that it took too long to extract data from the American Nautical Almanac to get a fix. P. V. Weems suggested that a big burden of computation could be transferred from the navigator to the almanac office if the Greenwich Hour Angle in arc replaced the right ascension in time.²⁶ In spite of limited staff, the office published supplements and made minor additions into the American Nautical Almanac beginning with 1929 and continuing through 1934. An experimental air almanac was issued in 1933. In 1940 permission was given to increase the staff of the NAO and start a crash program to design and publish an almanac to meet the needs of air navigators. There had been enough aerial navigation to find out what was required of an almanac, and the aerial navigators were in general a small group of carefully selected and highly educated young men. It was therefore possible to make an almanac on the basis of what was then considered the ideal almanac without much regard to the past. The desirable features included having all the astronomical data for a single day on a single sheet, tabulated at a suitable short time interval, and with convenient interpolation tables. The emphasis was always on doing as much calculation for the navigator as possible. When the American and British Air Almanacs were unified in 1953, there were some minor adjustments that did even more.

An annual Air Almanac was issued starting in 1941. It was first issued in three volumes per year of four months each (with patriotic red, white, and blue bindings²⁷); in 1977 it was issued in two volumes per year for six months each, and as of 1987 it has been issued as one annual volume. Sky Diagrams were issued separately for a few years, and were so enthusiastically received that they were incorporated into the volume.

Surface navigators quickly adopted *The Air Almanac* because of its ease of use.²⁸ This suggested that a changed design might improve the ease with which *The Nautical Almanac* could be used. In order to study this subject, the Naval Observatory included in the *Nautical Almanac for 1947* a questionnaire for mariners. The U.S. Institute Of Navigation had an Almanac Committee. It considered the comments received and a sample of pages from the Observatory. In October it sent a report to the Naval Observatory. In December the USNO began to prepare a preliminary sample of current ideas for a 1950 Nautical Almanac. This was sent to as many members of the ION as were deemed interested, for reaction, constructive criticism, and suggestions. Clemence was in charge.²⁹

As a result, *The Nautical Almanac for 1950* and onward was designed along the same lines as *The Air Almanac*: all the data for three days presented on facing pages, lookup tables to reduce the GHA in a separate section, and correction tables in critical value format on the inside covers.

As of 1998, at the direction of the RAF, HMNAO ceased publication of *The Air Almanac* for navigation and created a new one that serves an entirely different purpose, providing information on illumination and light levels.

Other Products: Printed

We have now discussed our three “mainline” continuing annual products. There is currently a fourth printed annual publication entitled *Astronomical Phenomena*. According to the annual report for 1951, “extracts from The American Ephemeris, with a small amount of supplementary material, are now published separately under the title Astronomical Phenomena. The contents consist primarily of material of interest to the general public, which was formerly supplied in mimeographed form or by correspondence; the separate publication is primarily for economy, permitting the users instead of the Observatory to bear the cost of distribution.” The first issue was for 1951 and coincided with the revision of *The Nautical Almanac*. The intent has been to publish it three years in advance of the cover date for planning purposes, but right now it is just two years ahead. It was for some time a joint publication with HMNAO, but they have now stopped marketing it separately.

There are other products with a significant lifetime, but are issued irregularly or have been discontinued.

When Newcomb began his grand project to redo all the planetary theories and to redetermine all the astronomical constants, in 1879 he started

a series to publish the results, titled *Astronomical Papers Prepared for the Use of the American Ephemeris and Nautical Almanac*. Generally known as "The Astronomical Papers", the most recent part was published in 1987, and while it is not officially terminated, it seems unlikely to continue. In parallel, *Publications of the United States Naval Observatory, Second Series* started in 1900 to publish astrometric observations and data, the most recent part appearing in 1992.

The Coaster's Nautical Almanacs were devised as an experiment by Newcomb to meet a perceived need, but are so obscure that they are mentioned only in a few annual reports.³⁰ Before the American Nautical Almanac Office was established, American ships used reprints of the British Nautical Almanac made by a Mr. G. W. Blunt. It had many errors in it, which was one reason justifying establishing an official American office. In 1857, a contract was made with him to cease publication of his almanac and become an exclusive agent of our official one. When he retired in 1867, sales agents were appointed in major seaports, and later sales were opened up to any dealer, although keeping the accounts was a major burden to the NAO. Sales fell off by a third from 1876 to 1883, supposedly because fewer American ships were in service, but Newcomb suspected it was actually because numerous companies were reprinting portions of the official almanac to sell cheaply for advertising purposes, and they were popular on ships plying a coastal trade.

Newcomb felt that since the Government had established the Hydrographic and Nautical Almanac Offices for the purpose of supplying navigators with all necessary scientific data for navigation, an almanac for the coastal trade should be issued. But in order not to compete with private enterprise, all known publishers of private almanacs had to agree to cease publication if an official almanac were issued. All but one did, that one being John Bliss & Co. of New York, nevertheless in 1884 an experimental American Coaster's Nautical Almanac was issued, followed by separate Atlantic Coaster's and Pacific Coaster's Nautical Almanacs in 1885. In addition to astronomical data, they contained information on tides, lists of lighthouses, and other information of use for coastal navigation. By 1891, it appeared that the experiment had failed, as the private publishers continued to produce cheap or free reprints for advertising and sales of the official almanac were never the great quantity expected. They were never discussed in the annual reports after 1891, though they appeared in the annual publications list until 1907 or 1908. The story is of interest to us now because we are today in a similar situation where copies of *The Nautical Almanac* are

being reprinted and sold privately even though British authorities hold the copyright.

The Ephemeris for the Bureau of Land Management (BLM), Department of the Interior, is the next discontinued publication. The annual report for 1959 stated that the Nautical Almanac Office had undertaken its preparation beginning with the issue for 1960. This was a publication founded in 1909-1910, and formerly prepared within that agency. Federal cadastral surveyors using solar attachments needed the data contained in *The Ephemeris* for determining bearings from astronomical observations. The BLM asked the NAO to take it over, apparently because their expert retired or died. In 1985, changes in our computer systems required major changes in the computational software, and the BLM decided that since use had declined so far, and other devices and calculator software on the market (such as *The Almanac for Computers* described later) could do the job, they would no longer support it. The last edition was for 1987-88.

Supplements and Circulars on solar eclipses are the final discontinued series. Even before the first volume of the *Ephemeris* was published, the NAO published predictions of a solar eclipse in 1851. Solar eclipses were of great value because the observations gave valuable information on the orbital elements of the Moon, up until the mid-1950s. After that, they gave valuable information on the limb of the Moon and the diameter of the Sun. The Navy sent expeditions to all total solar eclipses that could be profitably observed before World War II, and some afterwards. The American Nautical Almanac Office had charge of the eclipse work for all the almanac offices of the world until recently. Before the era of personal computers, the calculations for predictions were quite long and tedious, but a natural outgrowth of the work of the NAO. To encourage observations, supplements to the *American Ephemeris* were issued. The USNO began an irregular series of Circulars in July 1949, and many of them contained the information on solar eclipses previously issued in the supplements. The number of eclipse Circulars and the quantity of detail therein increased over the years, then they were discontinued in 1989 as a cost-saving measure. Only the basic information still appears in the annual almanacs.

There have also been important publications for navigators and astronomers that are not periodical, such as the two sets of Sight Reduction Tables for Marine Navigation (H.O. 229) and for Air Navigation (H.O. 249)³¹, done for the Hydrographic Office in cooperation with the British Nautical Almanac Office, and *Planetary and Lunar Coordinates* that is done every 20 years or so.

Other Products: Electronic

In consideration of the availability of computers and the Internet, we have started rethinking how we supply not just information, but services to the community. Other speakers will cover this in more detail, but for completeness I want to include here a mention of some of them. A more thorough discussion will be the topic of other papers in this Symposium.³²

Since the introduction of mechanical calculators, the NAO had distributed data on punched cards, and then magnetic tape. We also did some types of specialized calculations. As personal calculators and computers began to appear, there was a need to provide information tailored for them. The *Almanac for Computers*, 1977-1990, was designed to facilitate the applications of digital computers and small calculators to problems of astronomy and navigation which require coordinates of celestial bodies.³³ Fixed-interval tables, requiring interpolation, are replaced by concise mathematical expressions for direct calculations. The expressions were polynomial approximations fit to the tables, both navigational and astronomical. In the second edition, expressions were introduced to allow calculation of certain quantities for intervals greater than the current year. It was primarily a printed product, but the coefficients were also available on floppy disk or magnetic tape. It was discontinued when technology permitted the distribution of data and an executable file together.

The first computer almanacs of this form were introduced around 1986-1988, and were designed to do calculations using a supplied ephemeris that defined the valid time interval. The Floppy Almanacs,³⁴ good for just a few years each, were first, followed by the Interactive Computer Ephemeris (ICE) that had a longer ephemeris. Although they are still available from private sources, the NAO ceased supporting them when we introduced better products in 1993 and 1995. Two products were developed for certain microcomputer systems. MICA (Multi Year Interactive Almanac)³⁵ is the computerized complement to *The Astronomical Almanac*, while STELLA, (System To Estimate Longitude and Latitude Astronomically),³⁶ for DoD use only, is a counterpart to *The Nautical Almanac*. Each has a limited ephemeris.

As of 1996, the Astronomical Applications Department has a public Web site that provides information on our products and services, and can automatically handle many of our correspondence requests. As this seems to be an important future medium of communication both for DoD and general

use, we are investigating ways to expand and tailor our site to complement our printed publications.

In the continuing spirit of consulting with our customers before making changes, we enclosed a mail-back survey with *The Astronomical Almanac for 1999*, and also had a very detailed version up on the Web. We were interested not only in what portions of the publication are being used, but also whether an electronic complement or substitute would be acceptable. The results from several hundred responses indicate an overwhelming desire to retain the printed version no matter what. The respondents do not yet trust electronic media for ease of use, nor stability of the technology, in particular for archival purposes.

Conclusion.

The products of the Nautical Almanac Office have changed quite a lot over the long run. The evolution of our products is accelerating, and we are often asked whether we are keeping up with the evolution of technology. We place our mission at the highest priority. I close with some words from my predecessor, LeRoy Doggett:

By the 1980s some people regarded ephemeris offices as obsolete producers of paper products in an age of electronic information. Electronic methods of navigation were becoming much easier and, in many cases, more reliable than traditional celestial navigation. But at the same time, the offices were facing ever increasing public demands for information.

Today, with the market awash in astronomical software, someone needs to set a standard for scientific excellence. It is a role the ephemeris offices are uniquely qualified to fulfill.³⁷

Notes

1 Unless otherwise noted, all information on the almanacs and their contents is taken from annual reports of the Nautical Almanac Office, annual reports of the U.S. Naval Observatory, prefaces in the annual volumes, or reports of Commission 4 on Ephemerides within the Transactions of the International Astronomical Union that are published after each General Assembly.

2 David A. Kronick, "Almanacs and Annuals", in *A History of Scientific*

& Technical Periodicals, The Origins and Development of the Scientific and Technical Press 1665-1790, Second Edition, Scarecrow Press, Inc., 1976.

3 See "Finding the Longitude" in *Greenwich Time and the discovery of longitude*, Derek Howse, Oxford University Press, 1980, Appendix I, pp. 192-198. Also, Seymour L. Chapin, "A Survey of the Efforts to Determine Longitude at Sea, 1660-1760, Part II: The Use of Celestial Bodies", NAVIGATION, *Journal of the Institute of Navigation*, March 1953, p. 242.

4 P. K. Seidelmann, P. M. Janiczek, and R. F. Haupt, "The Almanacs - Yesterday, Today and Tomorrow", NAVIGATION: *Journal of The Institute of Navigation*, Vol. 24, No. 4, Winter 1976-77, pp. 303-312.

5 Craig Waff, "Navigation vs. Astronomy: Defining a Role for an American Nautical Almanac, 1844-1849", These proceedings.

6 Ibid.

7 9 Stat. L., 374, 375, CHAP. CLII. - An Act making Appropriations for the naval Service for the year ending the thirtieth of June, one thousand eight hundred and fifty. Text and background taken from "U. S. Naval Observatory [1809-1948]", a typescript first narrative prepared by Commodore J. F. Hellweg. QB82 U7U8 in the U. S. Naval Observatory Library.

8 Marc Rothenberg, "Observers and Theoreticians: Astronomy at the Naval Observatory, 1845-1861", *Sky With Ocean Joined*, Proceedings of the Sesquicentennial Symposia of the U.S. Naval Observatory, Edited by Steven J. Dick and LeRoy E. Doggett, U. S. Naval Observatory, Washington, D.C. 1983.

9 According to Hellweg, *op. cit.*, "On September 20, 1894, the Secretary of the Navy, availing himself of the authority granted in the act of March 3, 1857, issued a regulation making the Nautical Almanac Office a branch of the Naval Observatory. In a departmental decision rendered January 19, 1905 (File 9449-04 and 17626 Navy Department), it was held that the Nautical Almanac Office is not a separate shore station, and since that time its status has been that of a department of the Naval Observatory."

10 Synopsis of the Report of the Superintendent of the United States Naval Observatory for the Fiscal Year Ending June 30, 1909.

11 Wallace J. Eckert, "Air Almanacs", *Sky & Telescope*, Vol. IV, No. 1,

Nov. 1944.

12 Edgar W. Woolard, "The Centennial of the American Nautical Almanac Office", *Sky and Telescope*, Vol. XI, No. 2, pp. 27-29, Dec. 1951.

13 Synopsis of the Report of the Superintendent of the United States Naval Observatory for the Fiscal Year Ending June 30, 1908, p. 14.

14 Arthur L. Norberg, "Simon Newcomb's Role in the Astronomical Revolution of the Early Nineteen Hundreds", *Sky With Ocean Joined*, Proceedings of the Sesquicentennial Symposia of the U.S. Naval Observatory, Edited by Steven J. Dick and LeRoy E. Doggett, U. S. Naval Observatory, Washington, D.C. 1983.

15 Report of the Office of "The American Ephemeris" to Commission 4, Transactions of the International Astronomical Union, Vol. VII, Seventh General Assembly held at Zurich, August 11 to August 18, 1948. Cambridge University Press, 1950.

16 Seidelmann, Janiczek, and Haupt, *op. cit.*

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THE ASTRONOMICAL APPLICATIONS DEPARTMENT TODAY

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Introduction

The Astronomical Applications (AA) Department of the U.S. Naval Observatory (USNO) is the parent organization of the U.S. Nautical Almanac Office (NAO) established in 1849. The scope of activities involving almanacs has expanded dramatically over 150 years, in ways in which our early predecessors could never have imagined. This paper will provide an overview of the department, with the primary focus on the its current mission. Today, the AA Department provides practical astronomical data via a broad spectrum of products and services, and has an active research component aimed at supporting and improving these products.

Brief History

Just prior to 1990, the Nautical Almanac Office was one of three scientific departments of the U.S. Naval Observatory. The office employed a staff of approximately 20-25 people engaged in production of the printed almanacs, development of computer almanacs, research, and management of USNO's computer resources. In 1990, the decision was made to reorganize the NAO, splitting it into two new departments: the Astronomical Applications Department and the Orbital Mechanics (OM) Department. The goal of the reorganization was to separate research from production. The new AA Department was tasked to focus on delivery of products and services, with a special emphasis on satisfying U.S. Department of Defense needs. The OM Department was tasked to undertake research and development projects in orbital dynamics, involving both natural and artificial bodies. The AA Department also inherited the computer management responsibilities for USNO. Two things about the new AA Department's organization were particularly noteworthy. First, responsibility for the printed almanacs was given to a "new" Nautical Almanac Office, reduced to the level of a division. Second, responsibility for computer-based products was given to the new Product Development Division. USNO management at that time perceived growing importance of

the computer almanacs, and placed them on par, organizationally, with the printed almanacs.

The face of the AA Department changed for the first time as the result of another USNO reorganization in 1994. The OM Department was disbanded, and its personnel distributed to other USNO departments. The AA Department added two new staff members (actually former NAO staff) as a result of this change. Furthermore, the USNO computer management responsibilities were removed from the AA Department and relocated in a newly established Information Technology (IT) Department. This latter change had an especially positive impact on the AA Department, as computer management for USNO had long taken considerable resources away from the department's core mission work.

A relatively minor organizational change in 1996 completed the current organization of the AA Department by establishing the Dynamical Astronomy Division. The new division, staffed by existing members of the department, was tasked with performing research in dynamical astronomy. Most of this research is applied research, aimed directly at supporting and improving department products.

Mission

The current mission of the AA Department can best be summarized by its (unofficial) mission statement:

The Astronomical Applications Department of the U.S. Naval Observatory computes, from fundamental astronomical reference data, the position, brightness, and other observable characteristics of celestial bodies, as well as the circumstances of astronomical phenomena. This information is of critical importance to navigation, military operations planning, scientific research, surveying, accident reconstruction, architecture, and everyday activities. The products of the AA Department—publications, software, algorithms, and expertise—are used by the U.S. Navy and the other armed services, civilian government agencies, the scientific research community, and the public. Our products are regarded as benchmark standards throughout the world. The department also carries out a modest research program in celestial mechanics and positional astronomy to enable it to meet future needs.

Current Organization

Today, the AA Department is composed of three divisions. The *Nautical Almanac Office* is responsible for the four annual printed almanacs co-published with H.M. Nautical Almanac Office (HMNAO) of the United Kingdom (UK), and other printed products. The *Product Development Division* is responsible for the computer-based almanacs and for satisfying special astronomical software requirements primarily from the U.S. armed services. The *Dynamical Astronomy Division* carries out a research program to support the current operational mission and to meet the future needs of the department.

It should be noted that the "walls" that separate the divisions are actually rather thin. All divisions now assist in proofreading the pages of the printed almanacs. Staff of the Nautical Almanac Office assists the Product Development Division by testing the software almanacs. Applied research and advice from the Dynamical Astronomy Division has had an influence on virtually all department products.

Products

This section provides capsule descriptions of the main products produced or co-produced by the AA Department.

Printed Almanacs

i. *The Nautical Almanac*

The Nautical Almanac contains the astronomical data required for marine navigation. Most data on the main pages are tabulated at hourly intervals to a precision of 0.1 arcminute. The main pages contain the Greenwich hour angle and declination of the Sun, Moon, and navigational planets; the Greenwich hour angle of Aries; positions of the navigational stars; rise and set times of the Sun and Moon for a range of latitudes; and other data. Each edition also contains a sight reduction table, sight reduction formulas, and various correction tables for sight reduction. *The Nautical Almanac* is required, both by Navy policy and U.S. law. Under the current cooperative agreement, most of the volume is prepared by HMNAO, which also holds a copyright to most of the book. Currently, approximately 13000 copies of *The Nautical Almanac* are printed in the U.S. by the Government Printing Office (GPO), which also handles public sales in the U.S. The book is distributed to the U.S. armed services under the terms of a cooperative agreement between USNO, the National Imagery and Mapping Agency (NIMA) and the Defense Logistics Agency (DLA).

There is also a UK printing of *The Nautical Almanac*. The Stationery Office handles public sales in the UK.

ii. *The Air Almanac*

The Air Almanac contains the astronomical data required for air navigation. Most data on the main pages are tabulated at 10-minute intervals to a precision of 1 arcminute. The main pages contain the Greenwich hour angle and declination of the Sun, Moon, and three navigational planets; the Greenwich hour angle of Aries; rise and set times of the Moon for a range of latitudes; and other data. Each edition also contains sky diagrams for each month; sunrise, sunset, and twilight tables; and positions of the navigational stars. The AA Department prepares most of the book. Currently, approximately 11000 copies of *The Air Almanac* are printed in the U.S. by the GPO, which also handles public sales in the U.S. The book is distributed to the U.S. armed services under the terms of the cooperative agreement between USNO, NIMA, and DLA. Beginning with the edition for 1998, HMNAO introduced a new publication, *The UK Air Almanac*, at the request of the Royal Air Force (RAF). *The UK Air Almanac* provides illumination data, but does not provide the main pages of navigational data or the sky diagrams present in the original *Air Almanac*.

iii. *The Astronomical Almanac*

The Astronomical Almanac contains precise ephemerides of the Sun, Moon, planets, and satellites, data for eclipses, and other astronomical phenomena for a given year. Most data are tabulated at 1-day intervals. The book includes geocentric positions of the Sun, Moon, planets, and bright stars; heliocentric positions of the planets and their orbital elements; universal and sidereal times; daily polynomials for the Moon's position; physical ephemerides of the Sun, Moon, and planets; elongation times and differential coordinates of selected satellites of the planets; rise, set, and transit times of the Sun and Moon; eclipse data and maps; tables of reference data for various celestial objects; useful formulas; and other information. Under the current cooperative agreement, approximately half of the volume is prepared by the AA Department, and the other half by HMNAO. Currently, approximately 6000 copies of *The Astronomical Almanac* are printed by the GPO, which also handles public sales in the U.S. The Stationery Office handles public sales in the UK.

iv. *Astronomical Phenomena*

Astronomical Phenomena is an inexpensive booklet containing a preprint of data from *The Astronomical Almanac*. It contains the calendar; anniversaries and festivals; chronological eras and cycles; equinoxes and solstices; phases of the Moon; visibility and configurations of the planets;

eclipses; equation of time and declination of the Sun; rising and setting of the Sun and Moon; and positions of Polaris. The publication is of particular interest to calendar makers and to the U.S. National Weather Service. Most of this publication is prepared by HMNAO. It is printed by the GPO, which also handles public sales in the U.S.

Software Almanacs

i. *Multi-year Interactive Computer Almanac (MICA)*

MICA^{1,2} is an executable application program that provides high-precision astronomical data in tabular form for a wide variety of celestial objects. MICA calculates, in real-time, much of the information tabulated in *The Astronomical Almanac*. However, MICA goes beyond traditional printed almanacs by enabling the user to calculate data for user-specified locations at user-specified times within a long time interval. The first version of MICA, released in 1993, covered the years 1990 through 1999. The current version (1.5), released in 1998, is valid for a sixteen-year interval (1990-2005). Designed primarily for professional applications, MICA is intended for users familiar with the terminology and concepts of positional astronomy. It is available in editions for personal computers with Intel processors and Microsoft operating systems, and for Apple Macintosh systems. The current version of MICA was produced in partnership with Willmann-Bell, Inc. The AA Department produced the software and wrote the user manual. Willmann-Bell published the product and sells it as a hardcover book (user's guide) with a hybrid CD-ROM containing both editions of the software.

ii. *System to Estimate Latitude and Longitude Astronomically (STELLA)*

STELLA^{3,4}, released in 1995, is an executable application program that automates virtually all of the computations required for celestial navigation. It is the first product produced by USNO that not only computes the astronomical data needed for celestial navigation, but also utilizes these data, along with sextant observations, to determine position at sea.

STELLA performs six major tasks for the navigator: almanac, position update, rise/set/transit/twilight, gyro/compass error, sight planning, and sight reduction. It is based on several new mathematical approaches to celestial navigation. These include new developments for the sailing formulas, a rigorous method of computing a celestial body's position in the sky, a new algorithm for rise and set predictions for a moving platform, and new, flexible ways of combining observations to form a fix. As a result, STELLA carries out celestial navigation from a unique and computa-

tionally correct approach. STELLA's computations are performed to one-arcsecond precision—about 30 meters on the surface of the Earth—far exceeding the accuracy attainable by hand-held sextants. Even with hand-held sextants, the improved precision of STELLA's calculations and the options it provides the navigator are likely to result in better fixes.

STELLA was developed by the AA Department in response to a specific U.S. Navy requirement. The U.S. Coast Guard also adopted it in 1996 for use aboard all of its ocean-going vessels. STELLA is available only to the U.S. armed services for official use, but the new, underlying methods used in the software have been placed in the public domain through a series of three papers^{5,6,7} that were published in the American journal, *Navigation*.

Other Software Products

i. *Naval Observatory Vector Astrometry Subroutines (NOVAS)*

NOVAS⁸ is an integrated package of source-code modules that can compute a wide variety of common astrometric quantities and transformations. The package can provide, in one or two module calls, the instantaneous coordinates (apparent, topocentric, or astrometric place) of any star or planet. At a lower level, NOVAS also provides general astrometric utility transformations, such as those for precession, nutation, aberration, parallax, and the gravitational deflection of light. The computations are very precise. They are based on a vector and matrix formulation that is rigorous and consistent with recent International Astronomical Union (IAU) resolutions⁹. The NOVAS package is relatively easy to use and can be incorporated into data reduction programs, telescope control systems, and simulations. In fact, NOVAS is used by the AA Department staff to generate the data for many of the tables in *The Astronomical Almanac*. The NOVAS modules are available in both Fortran and C. They are available for download from the AA Department Web site.

ii. *Solar-Lunar Almanac Core (SLAC)*

The Solar-Lunar Almanac Core (SLAC) is a set of integrated software modules that provides information concerning the Sun and Moon, useful for operations planning, mission scheduling, and other practical applications. SLAC is not an executable application program. Rather, it is a self-contained source code "engine" designed for incorporation into larger software systems. SLAC provides equatorial and horizon coordinates of the Sun and Moon; times of rise, set, transit, and twilight; fraction of the Moon illuminated; and an approximate calculation of the amount of natural light reaching the surface of the Earth (the illuminance). SLAC was

produced in response to a specific U.S. Navy requirement and is available only to the U.S. armed services for official use.

The AA Department World Wide Web Site

In the summer of 1996, the AA Department initiated a major upgrade of its site on the World Wide Web (WWW). A significant amount of discussion and planning went into the design of the new site. It was decided from the outset that the site would distinguish itself by its content, not by extensive use of multimedia or sophisticated graphical design. Thus, department staff set out to provide as much frequently requested material as possible, and to make that material easy to access by the general public. The goal was to reduce the amount of staff time spent responding to the many routine phone, letter, and e-mail requests that the department receives daily for astronomical data and other information. Every division within the department contributes to the site.

The AA Department uses its WWW site to describe its products, services, and research results, and to direct customers to sources that distribute the products. The site also provides answers to frequently asked questions. The "crown jewel" of the site is the Data Services area. Here, users can compute, via interactive software, astronomical data tailored for particular dates and locations of their interest. The Data Services area allows users to compute, among other things, complete Sun and Moon data for a single day, yearly tables of rise, set, twilight, and Moon illumination, local circumstances of lunar eclipses, and horizon coordinates of the Sun and Moon. Even a limited Web-based version of MICA ("WebMICA") is provided. Most of the software underlying these services was reused from other AA Department products, such as MICA, STELLA, or SLAC.

The site has been a success. The AA Web server currently handles approximately 3000 user sessions, or more than 19000 hits, per day. The address of the AA Department home page is <http://aa.usno.navy.mil/AA>.

Research

This section provides capsule descriptions of key research projects that have or will have an impact on the operational products of the AA Department. Staff members are also engaged in other projects in areas as diverse as the dynamics of trans-Neptunian objects (TNOs), measuring changes in the solar diameter¹⁰, optical misalignment analysis¹¹, improvement of Global Positioning System (GPS) satellite orbits, and star formation in dwarf galaxies¹².

*Solar System Dynamics*i. *Newcomb*

Newcomb is the name of a new software system for generating high-accuracy, fundamental ephemerides of major solar system bodies, now under development in the AA Department. Prior to 1984, the printed almanacs utilized fundamental ephemerides that were produced "in house" at USNO. One of the goals of the Newcomb project is to regain that status. Furthermore, Newcomb will provide a valuable independent check on other high-accuracy ephemeris-generating programs, very few of which exist worldwide. It will also provide a valuable tool for performing basic research in solar system dynamics. Newcomb is being developed from first principles, both from an algorithmic and a programming perspective. The software is being written in the C++ language using modern object-oriented design techniques. This, in itself, should result in a system that is far easier to debug, extend, and maintain.

The software will be composed of three main modules. The *observations module* will process astrometric observations of various types, taken from various platforms including spacecraft. The *integration module* will be responsible for numerically integrating a sophisticated model of the dynamics of the solar system. This module is largely complete and exists as a stand-alone system called "Newton," which has already been used for investigations of the dynamics of asteroids and TNOs. Finally, the *parameter estimation module* will solve in a least-squares sense for the most probable set of model parameter values that minimizes the "observation minus computed" (O-C) residuals.

Current plans call for Newcomb to become operational during 2001¹³.

ii. *Asteroid Ephemerides and Masses*

Beginning in year 2000, a new set of minor planet (asteroid) ephemerides is required for *The Astronomical Almanac*. For this reason, an extensive set of observations, some going back into the 19th century, have been analyzed to provide new ephemerides and masses of some of the largest asteroids. Additionally, all asteroids that have measurable gravitational effects on their neighbors are being studied for possible mass determinations; the feasibility of such determinations depends on the strength of the dynamical interactions and the availability of good historical observations. The Smithsonian Astrophysical Observatory's Planetary Ephemeris Program (PEP)¹⁴ is being used to generate the new ephemerides and make the mass determinations.

Improved masses have already been determined for four asteroids^{15,16,17}. New high-precision ephemerides for 15 asteroids have been completed¹⁸, and will be made available to the astronomical community during 1999.

Other Projects

i. New Approaches to Celestial Navigation

As previously mentioned, new algorithms for celestial navigation were developed for use in STELLA. Given suitably accurate observing systems, these algorithms would provide sight reduction and positional fixes at the one arcsecond (30 meter) level of precision. Exploratory work to identify such a "suitably accurate observing system" is now underway¹⁹. The study is focusing on a hybrid system utilizing an automated star tracker (AST) operating in the far-red or near-infrared closely coupled to an inertial navigation system (INS). During periods of clear or partially clear weather, AST observations referenced to the local vertical and fed to the new navigation algorithms could provide high-accuracy positions of the vessel, day and night. These positions could also be used to continuously reinitialize the INS. The INS, in turn, could then provide vessel positions during times of high sky obscuration. Such a system could form an independent backup for a GPS-based navigation system.

ii. Algorithms for High Precision Astrometry

As astrometric requirements and measurement capabilities move from the milliarcsecond level to the microarcsecond level, it is necessary to assess the accuracy of current algorithms and improve them if need be. The astrometric algorithms, such as those implemented in NOVAS, are needed not only for the almanacs, but for other USNO programs as well. One recent study²⁰ compared two very different types of astrometric reduction—the approach based on angles, used for optical observations, and the approach based on interferometric delay, used for Very Long Baseline Interferometry (VLBI) observations. Despite their differences, both approaches should yield essentially identical results. A procedure by which VLBI algorithms can be used for optical observations was developed and implemented in software. This scheme allowed a large number of numerical tests to be performed, providing practical information on the differences between the angle-based and delay-based algorithms. The results of this study indicated that the differences between the two sets of algorithms in current use were less than one microarcsecond. This level of precision will be important for a new generation of astrometric satellites.

Summary and Conclusion

The Astronomical Applications Department of the U.S. Naval Observatory provides a variety of important and widely used astronomical data products and services. These products, produced or co-produced by the AA Department, carry the USNO seal throughout the world. *The Nautical Almanac* and STELLA are on board virtually every U.S. Navy ship, and are used on a daily basis. Furthermore, *The Nautical Almanac* is a near universal standard for civilian navigators. *The Astronomical Almanac* and MICA provide high precision astronomical data worldwide to intermediate and advanced users in a broad spectrum of technical disciplines. Air navigators still rely on *The Air Almanac* despite decreased use of celestial navigation from aircraft. Thousands of people from countries throughout the world visit the AA Department Web site each day, obtaining practical astronomical data for planning their activities. Finally, research conducted by AA Department staff has resulted in substantial, distinct improvements to the content of the products. This research has also contributed to the general, archival body of scientific knowledge. The work of the AA Department is still as relevant today as the mission of the Nautical Almanac Office was 150 years ago.

Acknowledgements

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NEW TECHNOLOGY FOR CELESTIAL NAVIGATION

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Celestial Navigation in the Era of GPS

Just a month ago I attended the annual technical meeting of the Institute of Navigation in San Diego. Almost all of the papers presented there were about current and future applications of the Global Positioning System (GPS); the meeting was an inspirational gathering of the GPS faithful. It is not much of an exaggeration to say that today navigation is virtually synonymous with GPS. This is a development of the present decade, which has seen the completion of the GPS satellite constellation, the shutdown of other electronic means of navigation, and a drastic reduction in the prices of GPS receivers. For Department of Defense vehicles, GPS is the principal means of navigation. U.S. Navy and Marine Corps navigation policy states, "NAVSTAR Global Positioning System (GPS) is the primary external reference system for naval operations requiring POS/NAV and time data."¹

Yet GPS has operational characteristics and vulnerabilities (including jamming) that may render it unusable or unreliable under certain conditions. Much work is being devoted to developing strategies for GPS outages. Operational plans now must include the contingency that GPS will not be available at the most critical times — a somewhat ironic situation for DoD, which has spent (and continues to spend) billions of dollars on the system. Perhaps anticipating an over-reliance on a single type of "black box" navigation, Navy navigation policy also states, "Every platform/user with a validated requirement shall have a primary and at least one alternate means of position determination. The alternate means must be independent of the primary."²

Unfortunately, alternative electronic navigation systems such as Omega and TRANSIT have been decommissioned, and long-term operational support for others, such as LORAN and VOR/DME, is not guaranteed; in any event, the latter are not available worldwide. Some kind of alternative to GPS is needed to comply with Navy policy and provide prudent redundancy for navigation systems. Inertial navigation systems, which are now common on Navy ships and aircraft, are being viewed as

the answer. However, there is a complication. These systems are really only a very accurate form of dead reckoning, and they require periodic alignment to some sort of external reference system. That external system could be GPS, of course, but such a mode of operation does not provide a secondary means of navigation that is "independent of the primary."

The stellar reference frame is an alternative to GPS that could be used to align inertial navigation systems. After all, the stars define the most fundamental and accurate inertial system available. As we will see, combining celestial and inertial navigation is not a new idea. Of course, on or near the Earth's surface, a fundamental obstacle to celestial observations is cloud cover: a run of bad weather can separate star sights by a day or more. But an inertial navigation system provides an excellent bad-weather "flywheel" that can carry the stellar fix forward until new observations can be obtained. There is more to be said about the advantages of the celestial-inertial combination, and we will return to the topic later.

Celestial navigation is practiced on a daily basis on Navy vessels. Standard Navy practice relies on quartermasters skilled in the use of hand-held marine sextants and paper-and-pencil sight reduction techniques. The basic method has not changed much in a hundred years, although almanacs and other sight-reduction tools have become more convenient to use. Observations are limited to a few Sun sights during the day and a few star sights during twilight. Because observations with hand-held sextants have typical uncertainties of about one arcminute, celestial fixes are rarely more accurate than several nautical miles. This kind of celestial navigation may be good for "sanity checks" on GPS fixes, and may be useful in an emergency, but its accuracy and availability fall short of many current military requirements.

If celestial navigation is to assume a broader role in the modern Navy's high-tech environment, its limitations will have to be addressed: low accuracy (a few miles), limited time window for observations (horizon must be visible), and low data rate. The sparse amount of celestial data collected over the course of a day results from the use of a human (with other duties) as a detector and computer, the small number of target objects (usually just the Sun and bright stars), and restrictions on the sky area used (altitudes 15° to 65°). It turns out that all of these limitations are a consequence of the way in which celestial navigation is now carried out, rather than being fundamental to the technique. They are a result of the human-intensive observing and computing procedure we use, and in that sense are self-imposed. However, if we are willing to think a bit more

broadly about how celestial navigation could be performed, we find that these problems have technical solutions. In fact, as we shall see, most of the needed solutions are available "off the shelf."

Significant improvement to celestial navigation's accuracy and availability will require changes in both the observational hardware and the computational procedure used to obtain a fix. Let us look at the mathematical situation first.

A Child's Garden of Navigation Algorithms — And the Weeds

The calculations that are required for the reduction of a celestial sight, if performed by hand, are slow and error-prone, and discourage the human navigator from taking sights — more tedious work to do! The traditional procedure imposes several other not-so-obvious limitations on the observations. For example, because observations of the Moon and planets require a parallax correction, many navigators avoid these objects, despite the fact that in marginal conditions they may be the only ones visible. Because the Moon is so seldom used, the possibility of Sun-Moon fixes is effectively precluded. All of this argues, if an argument is needed, for a computer program to do the calculations. There are many on the market, some embedded in special-purpose navigational calculators. Any reasonably accurate algorithm, implemented in a user-friendly program, would encourage navigators to broaden their observational habits and obtain more sights.

Beyond this common-sense recommendation for automation of the calculations, it becomes necessary to consider the specific algorithms used. A wide variety of algorithms for celestial navigation are available in the literature. Within the last three decades, in particular, many papers on this subject have been published, the authors motivated by the availability of inexpensive computing power compact enough for even small boats. Some very innovative mathematical approaches to celestial navigation were formulated, and some of these schemes found their way into commercial software products. There are now perhaps a dozen exact solutions of a two-body fix (although I doubt whether these are all mathematically independent). Of course, no prudent navigator would rely on a fix using only two observations (unless no others were available) and these exact solutions are not readily extensible to the more common case of three or four sights. When there are more than two observations, the problem is overdetermined and least-squares techniques can be used. Several least-squares approaches to a multi-star fix have been published. One, by deWit,³ is

based on the plane geometry and straight lines formed by celestial lines of position near the estimated position, a direct mathematical translation of chart-based navigation. It was developed independently by our colleagues at Her Majesty's Nautical Almanac Office and is printed in the back of *The Nautical Almanac* and in the HMNAO publication *Compact Data for Navigation and Astronomy*.⁴ In fact, *Compact Data* now includes a PC diskette with software that implements it. The scheme is quite easy to understand and is very robust. Use of plane geometry is an approximation, of course, but the method is quite adequate for the accuracy of ordinary sextant observations. A later least-squares formulation, by Severance,⁵ is more mathematically straightforward in that it does not rely on a special geometric construction.

Perhaps the most elegant solution to the multi-body fix problem was published by Paul Janiczek of the (U.S.) Nautical Almanac Office in 1978. It is a vector-matrix approach that fits on one page.⁶ An extension of this method, which uses a Lagrange multiplier for normalization, was published in 1991 by Thomas and Frederic Metcalf.⁷

Thus, in 1993, when the Chief of Naval Operations (N6) gave the Naval Observatory the task of providing standard celestial navigation software for Navy fleet use — the STELLA project — we apparently had many choices for the basic algorithm. (And I have not given here a complete survey of all the possibilities.) Initially we were leaning toward use of the Metcalf & Metcalf algorithm. One of the aspects of the project that I got interested in was how to deal with the motion of the ship during the time that a round of sights was taken; we wanted STELLA to handle a “running fix” as rigorously as possible. As it turned out, consideration of this apparently small piece of the overall problem led me to devise a completely different formulation of celestial navigation, one that is now incorporated into STELLA.

I discovered that despite the wide variety in the previously published algorithms, the fundamental developments for all of them assumed two or more co-located observations, something that requires either a stationary observer or simultaneous sights. Neither, of course, is a realistic scenario. In the real world, the observer's position changes during the finite time required to make the observations, so use of any of these algorithms requires transforming a moving-observer problem to a fixed-observer problem. One frequently used procedure is the addition of a motion-of-observer correction to an observed altitude; another is advancing the observation's line of position on the plotting chart. The most important

weakness of such procedures is well known: they require data on the motion of the observer's ship over bottom (that is, in latitude and longitude), and the course and speed values used may not be accurate. The accuracy of these quantities is usually limited by our inexact knowledge of the local current. The errors involved are such that, for sights made with ordinary hand-held sextants, difficulties may arise for observations spread over more than about a half-hour. Of course, if the accuracy of the observations could be significantly improved, then an observing period of only a few minutes would become problematic. The possibility of better observational material was something we wanted STELLA to be able to handle. Fortunately, the observations themselves contain information on the actual track of the vessel, so it should be possible to make the sight-reduction procedure self-correcting. In principle, given enough observations, suitably distributed in time and azimuth, we should be able to obtain an estimate of the average over-bottom track of the vessel as part of the solution for the fix. In 1995 I published a development of celestial navigation that incorporates a moving observer as part of its basic construction.⁸ This approach correctly represents the propagation of positional error along the observer's track, considered to be a standard rhumb line (loxodrome) traversed at constant speed.⁹ Furthermore, the procedure allows, under certain conditions, recovery of information on the vessel's actual course and speed from the observations. This new algorithm, described briefly below, includes the observer's motion as an essential part of the mathematics of celestial navigation, rather than as an add-on. Additionally, because the algorithm is not based on lines of position, it does not preclude observations very close to the zenith, if the instrumentation allows.

Celestial Navigation as an Orbit Correction Problem

Suppose we are given a series of observations taken over an extended period of time from a moving vessel. Is there a way to mathematically develop celestial navigation that includes the vessel's motion in the problem from the outset? Further, can such a development allow us to exploit the observations to correct our initial estimates of the course and speed of the vessel, as well as to provide a fix for a given time?

Our problem is quite similar to "orbit correction" problems faced by astronomers who deal with the dynamics of solar system bodies. (See Figures 1 and 2.) Given a series of observations of some moving object in the solar system — an artificial satellite, a deep-space probe, an asteroid, or a planet — we want to be able to compute the position of the object at

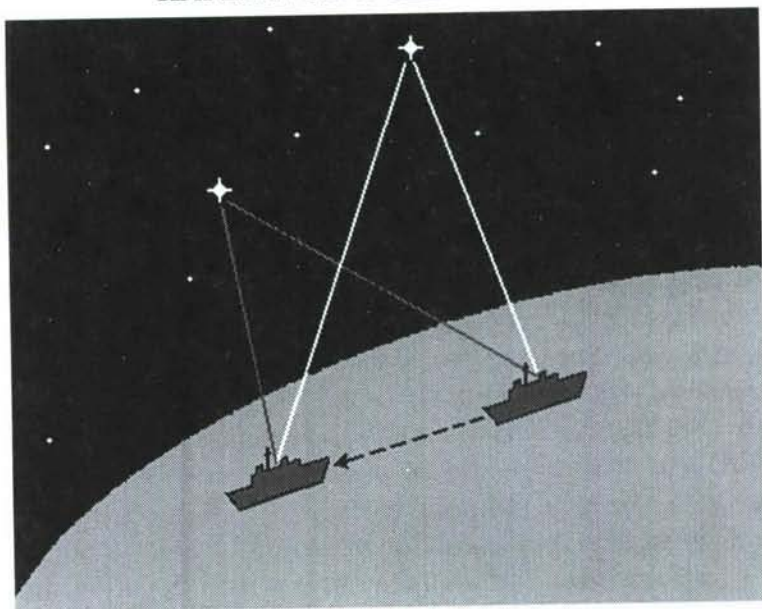


Figure 1. Navigation problem: moving observer, fixed celestial object(s).

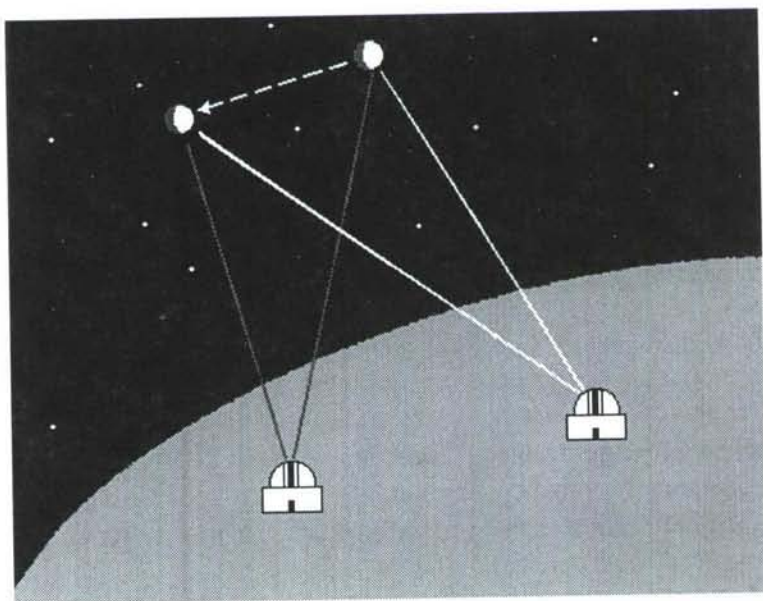


Figure 2. Astronomical problem: moving celestial object, fixed observer(s).

any given time. We know the laws of motion that the body obeys, but there is an infinite set of physically possible trajectories. Therefore, we must use the observations to determine the initial conditions, or orbital elements. The orbital elements are six parameters that specify the object's position and motion, in three dimensions, at a designated time. Once these six parameters have been determined, the object's position at any other time can be computed. The problem is the same regardless of what kind of observations are available. The observations may consist of simultaneous measurements of both celestial coordinates, or the observations may be only of range (distance). In the latter case we use a series of one-dimensional observations to solve a six-dimensional problem. As long as we have at least six observations (suitably distributed) the problem is solvable.

The running fix problem in celestial navigation is analogous. The moving object of interest is the observer's ship. The fact that the observations are taken *from* the moving object rather than *of* the moving object does not change the nature of the problem. However, in celestial navigation, the problem is four-dimensional rather than six-dimensional because ships are constrained to move over the two-dimensional surface of the Earth. The sailing formulas for rhumb-line tracks are the "laws of motion." We have a series of one-dimensional observations — sextant altitudes — from which we wish to determine, for a given time, the four "orbital elements" of the vessel: latitude, longitude, course, and speed. Once these have been determined, the vessel's position at any other time can be computed. As long as we have four or more observations, well distributed in azimuth and time, the problem is solvable.

The orbit correction problem is usually dealt with through a process called differential correction, which uses linearized equations in a least-squares formalism. This requires that we have some initial knowledge of the trajectory of the object of interest, which is almost always the case in both astronomy and navigation. This allows us to make a reasonably accurate estimate of the value of any observed quantity (e.g., declination or altitude) for any given time. The small difference between the observed value and the computed estimate can be accounted for by corrections to selected parameters in our *a priori* model of the object's motion.

Of course, a ship does not follow an exact rhumb-line course at constant speed, but is subject to random variations in wind, current, and steering. A vessel's path over bottom is a somewhat irregular line. The method of least squares, applied to this problem, assumes that the ship's excursions

from a rhumb line have a normal (Gaussian) distribution, even though that is unlikely to be rigorously true. Given a sufficient number of observations, the algorithm yields the parameters for a kind of average rhumb-line track over bottom, which is, presumably, what is desired. More problematic are systematic changes in the current or wind that occur over time scales of hours. In such circumstances the ship's track may not be well represented by a single constant-speed rhumb line. However, if the ship's track can be modeled as a series of connected rhumb lines, then a generalization of the algorithm can be used.¹⁰ The generalization, which is included in STELLA, allows observations taken over multiple voyage legs to be combined into a single solution.

The algorithm has been extensively tested using artificially generated data, both with and without random errors. Many examples found in navigation texts have been reduced again using it, and the results compared with other sight-reduction algorithms. Additionally, because STELLA was tested before release on board deployed Navy vessels, the method was checked in real-world applications. The algorithm works well and is robust. Statistical correlations among the parameters being solved for are usually low. The tests with perfect artificial observations have demonstrated the mathematical correctness of the algorithm.

However, the full power of the procedure has probably not been used so far in practice. Consider the traditional round of sights, in which a small number of observations (usually three to five) are taken within a short period of time, in twilight, and reduced to determine a fix. The uncertainties of hand-held sextant observations from a moving ship are such that almost any sight-reduction procedure is adequate for this case, and the algorithm described above does not have significant practical advantages over others. Course and speed corrections cannot be determined with such a limited observation set, and STELLA will not attempt to do so. For such cases, all reasonable algorithms give essentially the same answer.

The advantages of this new algorithm become evident when navigational practice is extended beyond the usual twilight round of sights or noon Sun line. Even with ordinary hand-held marine sextants, more flexibility in navigational procedures is possible than is usually practiced. For example, at high latitudes, long periods of twilight allow for extended sets of observations. Sun-Moon fixes are geometrically possible during about half of all days. Sun or Moon observations from early or late in the day can be combined with twilight observations. Observations of the stars and planets are possible at night near full Moon when the sky is bright enough to

make the horizon visible. But exploiting the full advantages of the algorithm would probably require new hardware, for example, an automated star tracker with an artificial horizon that could observe all night, or, in the near infrared, during the day. This leads us to consider the prospects for applying new hardware technology to the task of taking celestial observations.

Improving the Observational Data

Before we consider some of the new hardware possibilities, we should be clear on what it is we need to measure. To obtain latitude and longitude using observations of stars, which are for practical purposes infinitely distant, the essential measurement is the angle between the star and the local gravity vector at an accurately known time. The determination of time at sea has, of course, an interesting history in itself, but for present purposes I consider precise timekeeping to be a solved problem.

The gravity vector is indicated by a plumb bob, liquid surface, or floating bubble. Aircraft sextants for many years used a bubble in the field of view to indicate the vertical direction. For a standard marine sextant, the horizon, which we assume is a circle orthogonal to the gravity vector through the observer, provides a surrogate for a vertical reference on the instrument. This use of the sea horizon, the tangent to a liquid surface external to the vessel, has advantages that will soon become clear. It is interesting to note that if celestial objects were sufficiently close, the observer's position could be obtained without a determination of the local vertical — triangulation, similar to that used for conventional aids to navigation, could be used. The Moon is almost close enough for this (measuring the position of the Moon against the star background to one arcsecond would yield position on Earth to about one mile) but artificial Earth satellites would work much better (in principle, at least). However, for conventional stellar navigation, a gravity reference is needed.

Each observation ("sight") from a marine sextant consists of a measurement of the altitude of a celestial body above the visible horizon. There can be no dispute that the sextant is an extraordinarily successful instrument for its task. It is remarkable that the basic design of the marine sextant has not changed since the 18th century, when sextants (actually octants) replaced the cross-staff and back-staff. Over the past two hundred years, countless vessels of all sizes have sailed to all parts of the world using only a sextant for offshore fixes.

Occasionally there are initiatives to improve the sextant. The Nautical Almanac Office was involved in several such projects.^{11,12} Improvements included digital encoders to read out the angles, image intensifiers, and direct connection to a computer, which kept track of time. The most recent of such projects resulted in a prototype "automatic sextant" connected to a small calculator programmed to reduce the sights. Apparently the Navy did not choose to follow up on these developments. More recently, some commercial sextants have come equipped with modern night vision devices that have received favorable reviews. The night vision addition allows the horizon to be seen when it would otherwise be invisible. It's easy to imagine other possible improvements, such as automatic averaging of measurements or some form of image stabilization.

However, improvements to the sextant are unlikely to change the basic paradigm of shipboard celestial navigation, because the task would remain human-intensive. In contrast, most modern astronomical instrumentation is designed to remove humans from the observing process as much as possible, as a way of improving the efficiency of large telescopes and other expensive equipment. Such instrumentation, which could improve both the number and accuracy of observations made for celestial navigation, has not been exploited for shipboard use. However, some very advanced technology has been used for a related application — space navigation — and the same kinds of devices can, I believe, be profitably applied to surface and air navigation. A not unreasonable expectation for this technology is the acquisition of large numbers of star altitudes, day or night, at an accuracy approaching one arcsecond, equivalent to 31 meters on the surface of the Earth. This is comparable to GPS standard positioning accuracy.

Since the early days of the space age, automated celestial observing systems have been used on missiles, satellites, and planetary exploration spacecraft as an aid to navigation. Strategic missile systems such as Polaris, Poseidon, Trident, and MX have used compact star trackers in the powered phase of flight to determine the absolute orientation of the vehicle for the inertial guidance system. The more modern of these units achieve sub-arcsecond angular precision, a fact that has motivated some of the star catalog work done at the Naval Observatory over the past several decades. Many satellites use star sensors to determine attitude. The Space Shuttle has automated star trackers in its nose. Deep space missions may use star or Sun sensors en route for attitude determination, and science camera images of the target body against the star background as part of the

terminal navigation program. Star trackers have evolved from single-star to multi-star capability. Thus, space systems provide a substantial technological base in the automated measurement of stellar angles.

An example of a state-of-the-art star tracker is Lockheed's AST-201 system.¹³ Using what amounts to a standard camera lens with a charge coupled device (CCD) array in its focal plane, this unit can detect stars down to visual magnitude 7, the exact limiting magnitude depending on the unit's rotation rate. The star tracker contains its own star catalog and star pattern recognition software, and is designed to operate as a "black box" that receives stellar photons as input and provides digitized orientation angles as output. The orientation accuracy is several arcseconds about axes parallel to the focal plane. The unit is approximately 15 cm \times 15 cm \times 30 cm, including the lens shade, weighs about 4 kg, and is, of course, space qualified.

Would an automated star tracker be practical for surface or air navigation? In the late 1980s, Northrop designed a system called the Optical Wide-angle Lens Startracker (OWLS) that it packaged with an aircraft inertial navigation system.¹⁴ Using a holographic lens that could simultaneously image three 3° fields of view, each with its own focal plane detector array, the OWLS could deliver arcsecond-level orientation angles to the INS. The OWLS operated in the far red (R band, λ 0.6-0.8 μ m) so that it could detect stars down to R magnitude 5 at sea level in daylight. Clearly Northrop thought its system had broad application: "...astro-inertial navigation offers a practical solution for high-precision, autonomous navigation for surface ships, commercial aircraft, cruise missiles, strategic aircraft, remote piloted vehicles, and hypersonic vehicles."¹⁵ Although the system apparently never achieved such widespread use, its documentation presents a very clear picture of the possibilities.

As we have seen, compact, self-contained instrumentation is available for automated determination of star position angles. However, we have not yet discussed the other measurement required for latitude-longitude fixes: a determination of the local vertical. That leads us to again consider the role of inertial navigation systems.

Which Way is Up?

Determining the exact direction of the local gravity vector seems at first thought to be a trivial task. The measurement is fairly straightforward for a fixed location. Modern tiltmeters or accelerometers are sensi-

tive to the direction of gravity to arcsecond (or better) precision. It is true that for accurate position determination with respect to the Earth's reference ellipsoid, the apparent gravity vector must be corrected for "deflection of the vertical." This correction, which can amount to several tens of arcseconds, accounts for small-scale irregularities in the Earth's mass distribution. Fortunately, there are models and maps of the Earth's gravity field that are becoming more detailed and accurate all the time.

Unfortunately, other complications arise for a moving observer. Consider a hypothetical vehicle that is moving smoothly across the surface of the Earth. Assume motion with a constant heading, speed, and altitude, with negligible motion-related accelerations (aside from Coriolis forces, which are generally small and easily computable). In such a case, the gravity vector could be measured directly with any of the standard instruments. Using the STELLA algorithms, a series of measurements of the angles between the local gravity vector and an ensemble of stars could provide an autonomous determination of location at a given instant, as well as course and speed.

Of course, our hypothetical smoothly moving vehicle represents a rather rare, if not nonexistent, case. In real-world conditions, a moving vehicle is subject to a variety of accelerations from both internal and external sources. These accelerations cannot in principle be separated from that due to the Earth's gravity, so that any instantaneous measurement of the local gravity vector from inboard devices, such as tiltmeters or accelerometers, is highly contaminated. We can now understand why, for a sextant user, the sea horizon works better than a direct measurement of the local vertical: the horizon is not subject to the accelerations of the ship.

The problem of determining the true local vertical from a moving vehicle leads us back to inertial navigation systems, which have become ubiquitous on aircraft, missiles, and ships. As previously noted, these units can be thought of as an automated form of very precise dead reckoning. Each system combines a set of gyros, a set of accelerometers, and a computer. The unit must be initialized when the vehicle is at a known location. Using a continuous, rapid series of gyro and accelerometer measurements, the INS can compute the vehicle's instantaneous position and velocity at any later time. The system is thus self-contained after initialization. The accuracy of these systems varies widely, depending on size, cost, and acceleration environment. Typical specifications for aircraft

INS call for drifts within one nautical mile per hour of operation, but ship INS specifications are one to two orders of magnitude better.

As part of its navigation calculation, an inertial navigation system must *infer* the direction of the local vertical at each computation step. Due to gyro drift and other errors, this inference may not be as accurate as we would like (errors may accumulate at a rate of an arcsecond to an arcminute per hour), but it is likely to be better than any alternative. Thus, an INS can provide a usable, although not ideal, reference direction for astronomical measurements. Essentially, the INS becomes the plumb bob.

However, the astronomical measurements can be used to help correct certain INS errors — star tracker observations provide a link to an external reference frame that can be used to constrain the INS gyro drift. (The Kalman filter in the INS computer directly uses the star tracker data.)

Both orientation and position determinations are significantly improved. And, the INS will continue to provide navigation data (although of lesser accuracy) even if stars cannot be observed because of cloud cover. This kind of tightly coupled celestial-INS system has been most widely used for missile guidance systems, with great success. The combination is not perfect, since it is insensitive to at least one INS error mode (the Schuler oscillation),¹⁴ but it is a proven technology with a substantial engineering base.

Conclusion

Far from being a dying art, celestial navigation is moving into the 21st century as a highly sophisticated technology. Unfortunately, since much of the new hardware has been developed for space systems, many of the technological advances have been invisible to those outside the aerospace engineering community. I believe that much of the work that has gone into star trackers for space applications can be brought down to Earth to serve in new-generation air and sea navigation systems.

In particular, combining automated star trackers with inertial navigation systems seems to be a synergistic match. Inertial and celestial navigation have complementary characteristics. After initialization, INS is completely self-contained and has no coupling to any external reference system; celestial provides a direct link to the most fundamental inertial reference system available. INS units require initial alignment using positioning data from another source; celestial is completely autonomous. INS accuracy degrades with time from initial alignment; celestial fix

accuracy is not time dependent. INS units are oblivious to the weather; celestial is highly weather-dependent. Yet, despite their differences, both INS and celestial are passive, jam-proof, and in operational use are not dependent on shore or space components.

Tightly coupled celestial-INS systems have a history of success in certain applications. However, they have not been used on ships, even though modern sensors in the far red or near infrared would allow significant numbers of stars to be observed both night and day at sea level. It remains to be seen what modifications in design might be required for a shipboard environment, and whether these systems could achieve GPS-like accuracy afloat.

The possibility of other celestial-inertial configurations should also be explored. An accurate celestial-only navigation fix obtained without the use of the INS vertical reference would be a great advantage, but not one easily achieved. For example, adding a horizon sensor to a shipboard star tracker would allow for such fixes, but only when the horizon was a distinct line, and then with uncertain accuracy. Another possibility is using artificial satellites observed against the star background to form a navigation solution without a vertical reference. (Optical observation of satellites for navigation is being studied at Draper Lab.) It might even be possible to determine the local vertical from the effects of atmospheric refraction on star observations alone, although large numbers of very precise observations would be required.

When navigation methods are combined, the objective is to use the strengths of one technique to compensate for the weaknesses of another in a way that results in significantly higher accuracy and reliability. To this end, the Navy is in the process of deploying the Navigation Sensor System Interface (NAVSSI),¹⁶ a real-time computer that provides the shipboard navigator with "one stop shopping" for position, velocity, and heading information from GPS, INS, fathometer, gyrocompass, radar, and other sources. The STELLA algorithms are being added to the NAVSSI software, but there are no plans for any kind of star sensor to provide the kind of data the system needs to fully use those algorithms. As we have seen, there is hardware available to provide such data — why not use it?

As our defense forces rely increasingly on GPS, it is important that this dependence does not become a single-point-failure risk for military operations. Independent alternatives to GPS are needed and are required by official policy. Imaginative application of available technology can ensure that celestial navigation has as much of a role to play in the future

as it has in the past in helping to provide safe passage for our military forces worldwide.

NOTES

1. Chief of Naval Operations/Commandant of the Marine Corps joint letter Ser 09/1U500942 of 1 August 1991, p. 2
2. Ibid. A new navigation policy letter is being drafted, but the two statements quoted in the text are being retained.
3. C. DeWit, "Optimal Estimation of a Multi-Star Fix," *Navigation, Journal of the Institute of Navigation*, 24 (Spring 1997), 67-71.
4. B.D.Yallop and C.Y. Hohenkerk, *Compact Data for Navigation and Astronomy for the Years 1996-2000* (HMSO, London, 1995).
5. R. W. Severance, "Overdetermined Celestial Fix by Iteration," *Navigation, Journal of the Institute of Navigation*, 36 (Winter 1989-90), 373-378.
6. R. Watkins and P. M. Janiczek, "Sight Reduction with Matrices" (Forum), *Navigation, Journal of the Institute of Navigation*, 25 (Winter 1978-79), 447-448. (Despite the order of the authors' names, it was Janiczek that devised the method.)
7. T. R. Metcalf and F.T. Metcalf, "On the Overdetermined Celestial Fix," *Navigation, Journal of the Institute of Navigation*, 38 (Spring 1991), 79-89.
8. G. H. Kaplan, "Determining the Position and Motion of a Vessel from Celestial Observations," *Navigation, Journal of the Institute of Navigation*, 42 (Winter 1995), 631-648.
9. It was rather surprising that closed-form expressions for latitude and longitude as a function of time, for rhumb lines on the Earth's ellipsoid, were not available in the literature. Thus, deriving accurate sailing formulas was one of the first orders of business for the STELLA project. The formulas used in STELLA are described in G. H. Kaplan, "Practical Sailing Formulas for Rhumb-Line Tracks on an Oblate Earth", *Navigation, Journal of the Institute of Navigation*, 42 (Summer 1995), 312-326.
10. G. H. Kaplan, "A Navigation Solution Involving Changes to Course and Speed," *Navigation, Journal of the Institute of Navigation*, 43 (Winter

1996-97), 469-482.

11. S. Feldman, P. K. Seidelmann, and G. G. Barton, "Advances in Celestial Navigation," *Naval Engineers Journal* (August 1974), 65-76.

12. J. A. Decker, Jr., "Automatic Sextant," *Proceedings of the Forty-First Annual Meeting*, Institute of Navigation (June 1985), 111-117.

13. "AST-201 Star Tracker System Specifications, Rev. D," LMMS-F426359-D, Lockheed Martin Missiles & Space Advanced Technology Center (September 1998).

14. S. Levine, R. Dennis, and K. L. Bachman, "Strapdown Astro-Inertial Navigation Utilizing the Optical Wide-angle Lens Startracker," *Navigation*, Journal of the Institute of Navigation, 37 (Winter 1990-91), 347-362.

15. Ibid., p.362.

16. R. A. Greer, "The Navigation Sensor System Interface Project," *The Journal of Navigation*, 46 (May 1993) , 238-244.

ALMANACS: THE USERS' PERSPECTIVES

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The session entitled "Connections" highlights the connection between the Nautical Almanac Office and the users of our publications, which we publish jointly with Her Majesty's Nautical Almanac Office. To begin, we invited four distinguished speakers to give their own perspectives of the *Nautical Almanac*, the *Air Almanac*, and the *Astronomical Almanac*. The speakers represent diverse backgrounds, both civilian and military, and have expertise ranging from navigation to astronomical research. These speakers have all relied on our publications to conduct research or carry out their duty. Their perspectives of our publications are very important to us in the Nautical Almanac Office, since feedback from regular users allows the publications to evolve along with advances in research and technology.

It is always interesting to us to learn where one of our publications has been spotted. For instance, our publications may be found aboard a yacht, an aircraft carrier, a submarine, or a cruise ship; on an aerospace engineer's or architect's desk; in a public or law library; in an observatory, an air squadron ready room, or a military aircraft. In fact, you can even find a copy of our *Air Almanac* aboard Canadian, New Zealand, Australian, and Norwegian military aircraft. The users of our publications are a very eclectic group, although these four speakers are representative of the majority of our users: military and civilian surface navigators, air navigators, and astronomers.

The session will be completed with three more presentations to highlight the connections between our office and the international scientific community, and then the relationship between the Astronomical Applications Department, which contains the Nautical Almanac Office, and the other departments at the Naval Observatory, time and astrometry.

A VIEW FROM THE DECKPLATES

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U.S. Naval Observatory

As a U.S. Navy Chief Quartermaster, I have been engaged in ship navigation for nearly 30 years of active and reserve service. I've watched as electronic navigation technology has evolved from matching the "grass spikes" of the LORAN signals on a small oscilloscope screen, to the digital readouts of today's Global Positioning System (GPS). In fact, GPS is so advanced it provides position information in three dimensions: latitude, longitude, and altitude. That's quite a change considering the relatively short history of electronic navigation.

A Celestial Day at Sea

As a point of reference, I'd like to describe a typical day of celestial work at sea. Before each group of observations, in the morning or evening, sight planning is required. This is the calculation of the Local Hour Angle (LHA) of Aries and the selection of stars or bodies to be observed. For simplicity's sake, the LHA of Aries is the "longitude equivalent" of the celestial reference point.

Morning star time is about an hour before sunrise. If the horizon is clear and the sky is not overcast, there's an opportunity to make observations. I don't know how many times I've gotten up before dawn, completed the preparatory work, and had a hazy horizon. Or the times a high thin cloud layer obscured the stars at the wrong moment. These are things that can not be determined before nautical twilight.

Next is the morning azimuth, measuring the precise direction of the Sun at a given moment. A comparison of the gyrocompass heading with the true direction of the Sun will determine the gyrocompass error. The morning azimuth is accomplished about an hour after sunrise, with the Sun between 10 to 20 degrees above the horizon, for the best results.

A morning sunline, the observation of the Sun at mid-morning, is used to obtain a line of position (LOP). Normally one LOP from the previous fix is "advanced" (moved the same distance and direction that you have traveled) between observations. The junction of the advanced

LOP and the just-observed LOP is your location. The sunline observations between morning and evening stars produce what is called a "running fix." Allowing about a $1\frac{1}{2}$ hour minimum between observations, long summer days may permit multiple observations between morning stars and Local Apparent Noon.

Local Apparent Noon, or the Sun transit, is the mid-day observation for latitude. This observation is unique in that the exact latitude position will be calculated. With the exact time of the observation of the Sun at its greatest altitude, longitude can also be determined.

The afternoon sunlines are similar to the morning. Two and sometimes three observations are possible in the afternoon depending on the season.

The afternoon azimuth, about an hour before sunset, is a second check on the accuracy of the gyrocompass.

Evening star time is about forty minutes to an hour after sunset. Like the morning star observations, evening star observations are accomplished during the short period of time when both the horizon and the stars are visible.

Mathematics

We've made the observations, now what? Time to do some math—lots of math. Some of the calculations are in the familiar base 10, but most are base 60, solving time and arc calculations. A programmed navigation calculator can reduce the number of calculation steps, but its use still requires the same meticulous attention to detail.

The traditional method of sight reduction, or calculation, using *The Nautical Almanac* and sight reduction tables (Publication H.O. 229), takes about ninety minutes to do the approximately 120 calculation steps to solve for six star lines of position. These same calculations using *The Nautical Almanac* and a programmed navigation calculator take about 45 minutes, involving about 50 calculation steps.

In all, a navigator doing the calculations with the publications spends about seven hours per day taking celestial observations and performing the calculations. Using a navigation calculator the time is reduced to about four hours per day. Of course, this work is spread out between an hour before sunrise and about an hour after sunset.

The Digital Age

In navigation, the navigator has traditionally been trained to be skeptical, to confirm everything with another method or source of position information, such as use of the fathometer or another independent electronic navigation system. Double-checking things is second nature to an experienced navigator.

Navigators are among the last of the renaissance men, dabbling in various fields of study by virtue of their position. A navigator is a sailor, a mathematician, an oceanographer, a meteorologist, an astronomer, and may have interests in marine mammals and radio operation. We have information and skills in many disciplines but are generally not experts in any one field.

Technology is forcing navigators to face a new challenge. We are on the cusp of a transition from the "traditional" paper and pencil navigation to the digital age. Gone will be the meticulous chart corrections and massive chart inventories. Put a compact disk (CD-ROM) in the computer and the corrected charts will appear on the display. Push a few buttons and the ship's position will be displayed, and updated automatically.

These methods of navigation, the pencil/paper and the digital system, are not really compatible. The space designated for the chart table is not sufficient, along with existing electronics, to properly lay out a chart for navigation. The addition of a computer system will take a significant portion (about 25–40%) of the remaining chart table surface and severely limit one's ability to navigate by traditional methods.

The Down Side

The electrical systems on ships and aircraft are susceptible to failure. We take our technology into arduous environments; failures will occur. If electrical power is not restored before the battery backup fails, then all the gadgets and gizmos are useless. Even the process of changing the battery results in temporary loss of the system. How long does it take your electronic system or computer to recover from a momentary outage?

Our GPS system is based upon radio signals from satellites. What will happen if the increasing solar activity interferes with these signals? Or a swarm of meteoroids knocks some out of service? This was considered a possibility during the most recent Leonid meteor shower, emphasizing the need for celestial navigation skills and training in traditional methods.

Advances in Navigation

The Nautical Almanac Office has developed a computer program that does all the celestial calculations in moments. STELLA, the System To Estimate Latitude and Longitude Astronomically, replaces all of the meticulous steps of sight reduction and provides a nearly instantaneous solution after the data are entered. The time required for celestial navigation duties, using this program, has been slashed to a few minutes more than the time it takes to actually make the observation and enter the data into the computer.

The navigator's celestial workday can be less than two hours per day using this computer application compared to 4 hours using a navigation calculator or about 7 hours using the traditional manual calculations. The limiting factor of the navigator's workday will be the times that observations must be made.

Thoughts on Training

Careful steps must be taken to preserve traditional celestial navigation skills as technology progresses. The student navigator, learning celestial navigation today, will not learn the steps of the calculation by using the computer alone. When the computer system is not available, will that future navigator be able to determine the ship's position? Plot a safe course home? The ability to perform the calculations manually has saved many sailors and airmen; no computer in existence today would long survive or operate in a lifeboat environment.

In Closing

No matter how "advanced" our electronics become, there will be a time when the "old" way of doing things will be needed. The infamous Mr. Murphy's adage, "If anything can go wrong, it will," works at sea also. Will navigators of tomorrow be up to the task without all the electronics?

The final, simple point I wish to make is this—with a sextant, a source of accurate time, and a *Nautical Almanac*, I can find my way home. *The Nautical Almanac* has all the data and reduction tables needed to determine position. I will never go to sea without it.

CELESTIAL NAVIGATION BY U.S. CIVILIAN MARINERS NEAR THE END OF THE SECOND MILLENIUM A.D.

W. J. Brogdon, Jr.
Captain, USCG (ret)

When I learned celestial navigation over 40 years ago at the Coast Guard Academy, the *Nautical Almanac* was integral to sight reduction. We were required to learn Napier's rules and the formulae for the divided triangle, and to use *Ageton's* two tables, with "A" and "B" and "K - d" for all our sights for the first two years. We considered this as something between harassment and punishment. Afterwards, the instructors allowed us to use HO-214, and sight reduction became much easier. Although the *Air Almanac* and HO-249 were available, and we learned to use them, we used the more accurate *Nautical Almanac* for sight reduction. I continued to do so for many years. We young cadets never gave much thought to the source of the *Nautical Almanac* data, any more than we did the log trig tables. We assumed that both were quite accurate, an assumption that was well-placed, despite our uncritical acceptance.

I was navigator on my first ship, a cutter that depended entirely on celestial navigation for all but one of the North Atlantic ocean weather stations. I was Operations Officer on the second ship, and so on up the line, keeping up my competence in and teaching celestial navigation. Even aboard my last ship, Coast Guard Cutter *Dallas*, we used celestial navigation extensively in the Caribbean. That was in 1979 and 1980, and we didn't carry SATNAV or Omega, and the Global Positioning System was experimental and intermittent.

But this paper isn't about an old fud's experience with celestial navigation and the *Nautical Almanac*, rather about how it is used in the civilian community today. There are six sources of information in addition to *Almanac* sales: other publications, courses, equipment catalogs, license requirements, training schools, and cruises devoted to celestial navigation. The commercial market for a product or service is a most accurate measure of its usefulness, and research for this paper has revealed a lively industry that is providing goods and services to navigators who use sextants and almanacs.

Publications

There are over 50 books about celestial navigation available, and many of them are recent. Just one popular book, *Celestial Navigation for Yachtsmen* by Mary Blewett, sells about 2,500 to 3,000 copies per year, according to the publisher, International Marine. This is quite good for such a specialized book. The many others range from books with few sales to popular textbooks. As an aside, it seems that a significant number of people who learn to navigate by the stars feel compelled to write a book on how to do it. Some of these books reflect the limited knowledge of the authors, but new methods also beget new books on the market. Within the last year, International Marine has published *The Complete On-Board Celestial Navigator 1999-2003* by George Bennett, a book that includes a five-year almanac and sight reduction tables that are different from previous methods.

Ocean Navigator magazine is a thriving operation that features celestial navigation along with other navigation and piloting, electronic, and seamanship issues. It has a paid circulation of 43,000, which is strong for a special interest magazine. Each issue contains numerous advertisements for celestial navigation schools, nautical equipment, and computer programs. The magazine operates celestial navigation cruises on a regular basis. It has been published for over ten years.

The *Nautical Almanac* is critical to a large number of navigators. The U.S. Naval Observatory prints 14,000 copies, of which 4000 go directly to NIMA for Department of Defense distribution. We don't know exactly how many are sold, but it would be a fair estimate that the public buys over 9,000 copies of the USNO *Nautical Almanac*. With the included USNO Sight Reduction Tables, it gives a complete solution to a navigator with sextant, watch, short-wave radio, and plotting equipment. The commercial version, the blue-cover almanac, sells about 13,000 copies per year. In addition, USNO prints 10,000 copies of the Air Almanac, of which 6000 go directly to NIMA for DoD distribution. So there are some 30,000 Almanacs sold each year, primarily in the United States. Of course Her Majesty's Nautical Almanac Office sells large numbers, as well.

These printed versions remain useful, and indeed handier than a computer program for examining certain data. There's something to be said for the printed page, which presents a great deal of data in a clear, flicker-free font. You can examine a changing entry quite easily, particularly if you are interested in day-to-day trends. Bending down a

page and drawing a line under data of interest provides a system that is quicker to re-boot than any computer.

Equipment

There have been continuing developments in sextants to improve accuracy and ease of use. Sextants are available in two sizes to give a choice of weight and bulk. The newer whole-horizon mirror is popular for sun sights, while the traditional half-silvered mirror is better for faint stars and is in the widest use. There are nine models of metal sextants available from various manufacturers. There are two models of plastic sextants, of limited accuracy but suitable for emergencies. There are now night vision scopes specifically designed to fit sextants. These scopes extend the twilight period greatly, and promise with newer models to allow sights all night long.

The catalogs list accessory items such as chronometers, short wave radios, celestial navigation calculators, sight reduction forms, plotting sheets, cases, star charts, a commercial version of the Rude Star Finder, and surplus aircraft type sextants. Henry Marx's Landfall Navigation stocks a complete line of celestial navigation equipment, as well as an extensive list of radionavigation, piloting, and computer programs and equipment.

Celestaire, a company that is devoted to celestial navigation equipment and courses, reports a resurgence in interest in celestial navigation and in sextant sales. A few years ago sextant sales slumped to just over one-half their previous level. Now, as people are becoming aware of the need for a back-up to GPS, Celestaire is selling as many sextants as ever. The factory in China that produces the Astra line of sextants is operating at capacity. In most large ports, there is at least one well-stocked nautical equipment store that carries celestial navigation equipment and publications. The marine discount catalogs even carry sextants, plotting equipment, and publications.

Courses and Seminars

The U.S. Coast Guard Auxiliary and the U.S. Power Squadrons have offered celestial navigation courses for many years. There are many others available from private enterprise sources. David Burch's Starpath in Seattle offers classroom and home study courses, classroom instruction, sextants and equipment, and talks on celestial navigation. Ken Gebhart,

who owns Celestaire, offers courses and conducts seminars for people who want to learn the fundamentals of celestial navigation. He runs eight seminars at boat shows every year, and about 100 people attend each seminar. The celestial navigation seminar has been the best attended of all the seminars offered at the Strictly Sail show, for example. These are just a sampling; there are over 50 organizations offering some form of celestial navigation instruction to yachtsmen. This does not include Community Colleges, many of which offer classes in celestial navigation.

Sight Reduction Methods

There has been a steady progression of sight reduction methods. We used tabular solutions such as HO-229 until Hewlett-Packard introduced the scientific calculator around 1970. It became easier to work the formulae by calculator than to look up the values in a table. Then the programmable calculators came on the market; both Hewlett-Packard and Texas Instruments provided celestial navigation programs. These programs relied on the *Nautical Almanac*.

By the 1980s, various makers introduced small computers that used the BASIC language. The early versions of BASIC that handled decimal fractions were entirely suitable for sight reduction, using appropriate algorithms. I remember programming a little Radio Shack handheld computer and storing all the programs on a tape. Later I programmed a CP/M computer for celestial navigation; the programs were directly usable on IBM computers. So at this time, it became simple to solve the spherical trigonometry formulae with short programs for personal computers. All of these programs used the *Nautical Almanac*.

Around 1980, two specialized celestial navigation computers came on the marketplace. They included almanac functions and sight reduction, and remain on the market. The latest models are the Celesticomp V and the Tamaya NC-2000.

Next came the more sophisticated commercial computer programs using built-in almanac functions. Some of these were of questionable accuracy, and few of them stated the source of their almanac data. The Naval Observatory weighed in with the excellent *Floppy Almanac* and later the *Interactive Computer Ephemeris* programs. Though neither program was especially easy of data entry, they were from a most reliable source, which specified high accuracy for both of them. They used spherical trigonometry and thus allowed quick checking with any tabular

or calculator sight reduction method. These programs were landmarks in accurate, affordable sight reduction programs that incorporated sight correction, almanac, and sight reduction functions. The navigators plotted their sights on paper, as usual. These and various commercial programs actually began to increase the popularity of celestial navigation, by taking out most of the effort and potential errors in sight reduction. Ordinary DOS computers could handle them easily.

Today's commercial programs offer electronic plotting in addition to the above functions and are thus even easier to use. Some are stand-alone programs, but others are add-ons to expensive charting/electronic positioning programs. Users of these sight reduction methods including tabular ones continue to lack a practical method of averaging several sights of the same body for increased accuracy. The navigators who do recognize the advantages of averaging haven't developed a simple way to do so. They tend to use paper plots to solve many problems, but graph paper would have to be very large and with suitable graduations to be handy and accurate for this purpose.

Unfortunately, the greatest advance in celestial navigation accuracy remains unavailable to civilian users: the U.S. Naval Observatory STELLA program. The civilian community simply doesn't have access to a program based on a spheroidal earth and with such extremely accurate almanac data, or one that is so well adapted to a moving ship.

Licensing Requirements and Voluntary Certificates

Merchant Marine officers who sit for Ocean Licenses must demonstrate proficiency, at least on paper, with celestial navigation. In 1995, the latest year for which data are available, the U.S. Coast Guard issued 975 new licenses to people who qualified for Ocean route licenses. This in itself creates a significant demand for celestial navigation texts, training, and for the *Nautical Almanac*. In the same year, the Coast Guard issued 12,310 renewal Ocean route licenses. Since license holders must renew them every five years, this represents over 60,000 people who have demonstrated competence in celestial navigation when they first sat for an ocean license. Since the United States now represents a small fraction of world shipping, the worldwide total of people who have to learn celestial navigation is far greater.

U.S. Sailing in Newport, Rhode Island issues certificates to those who have demonstrated competence in boathandling and navigation. They

issue two classes of certificates for large sailboats: coastal and offshore. To earn the offshore certificates, candidates must demonstrate proficiency in celestial navigation as well as many aspects of sail handling and seamanship. People who earn offshore certificates can use them when chartering boats, or simply learn navigation for use aboard their own or friends' boats. There are 51 schools participating with the U.S. Sailing large sailboat program. The courses mentioned above, including the USCG Auxiliary and the US Power Squadrons, also issue certificates for those people who complete them successfully.

Contemporary Practice

While thousands of merchant marine officers have demonstrated proficiency in celestial navigation, the number of them who are actually using sextants for navigation is very small. This information comes primarily from interviews with ship pilots and ship's officers. It is so easy to use GPS that few ships' officers bother to use celestial navigation any more. They seem unaware of the hazards of total reliance on one electronic aid to navigation, despite numerous accidents. Modern ships have automated navigation systems that rely totally on GPS. The cruise ship *Royal Majesty* grounded near Nantucket on 10 June 1995 while the GPS data indicated that the ship was about 17 miles east of her actual position. So mesmerized was the watch officer with the "higher accuracy" of the indicated GPS position that he ignored the depthfinder, the radar, the Loran, and the sight of a lighthouse and a Loran tower on Nantucket Island.

The great drive behind automated navigation systems has not been to increase reliability by cross-checking aids to navigation, but to "reduce operator workload." This has succeeded beyond anyone's wildest dreams, in this case reducing the watch officer's navigation workload to zero. One wonders what he was doing that was more important than navigating the ship. Had any one of the ship's officers taken a celestial fix within the 24 hours prior to the grounding, they would have found that the ship's position was remote from that indicated by GPS.

The primary use of celestial navigation aboard large merchant ships seems to be as a seldom-used backup to GPS. This situation does not appear to be likely to change in the near future. Yet each ship continues to carry equipment and tables to allow celestial navigation should it be needed. One supplier of sextants arranged for a direct shipment from the

factory to a ship in Singapore to meet a time-critical need. He was apologetic to the buyer, and recommended checking them upon arrival.

"Don't worry," came the reply, "they'll probably never take the sextants out of the boxes."

The attitude is quite different aboard yachts on long passages. Ocean voyagers aboard yachts today use celestial navigation far more than any other group of marine navigators. Although most boats today carry GPS, the owners are reluctant to sail on a long voyage without a valid backup. *Ocean Navigator* recently reported the failure of both GPS receivers aboard a sailboat in the Pacific, and the subsequent scramble to find position. While many boats carry Loran for coastal navigation, the offshore backup overwhelmingly is celestial navigation. My activity in recent years to preserve Loran parallels my continued interest in celestial navigation. Coastwise or offshore, I never want to be totally dependent on one electronic aid to navigation.

Many people have learned to use a sextant and reduce sights in anticipation of a long voyage, and use the time at sea to develop skill with the sextant and in sight reduction and plotting. For some, the very idea of being independent of everything except time signals adds to the experience of the voyage. For others, using an old but reliable system of navigation carries its own charms.

Being at sea on a clear night on a boat or ship with only the running lights and a few dim instrument lights gives a magnificent view of the night sky that is seldom available ashore. It is a humbling experience to see and ponder about the creation and our place in it. As for me, I think of the Creator who gave us the beautiful and predictable lights that we use regularly in navigation. Sometimes I think of the work of observers and thinkers down through a long chain of centuries to grasp the extent of the universe and its workings. Those who based their work on the stars and planets developed the ability to predict celestial body positions to higher and higher accuracy, work that is so critical to our celestial navigation.

Most yacht navigators who use celestial navigation begin by taking sun sights. They typically have more trouble identifying stars and in obtaining star sights during the relatively short periods of twilight. The combination of an unfamiliar task, the rapid motion of a boat at sea, and cramped navigation stations all work against the learner. Boat motion makes it difficult to take accurate altitudes, and also affects sight reduction and plotting. It is most common to make errors in sight reduction and

plotting for the first few fixes, and working in a small space below decks while experiencing lively motion does nothing to make it easier. Those who stick it out find celestial navigation far easier after the first few days, but many give up after an early failure.

A certificate showing competence in celestial navigation has become something of a badge of honor among yachtsmen. While many undoubtedly qualify for certificates yet never use celestial navigation offshore, there are others who actually follow the dream, who make a long sailing voyage. The preponderance of these people carry equipment for celestial navigation. Many of them become quite skilled in taking and plotting sights. Others rely on GPS but want to carry a backup aboard, and that backup usually includes a *Nautical Almanac*. As one experienced delivery captain said, "I simply won't make a delivery on an offshore route without the sextant, a watch, and the tables."

Still Going

Today, celestial navigation shows a great dichotomy. Ships' officers, who must learn celestial navigation, seldom use it. They rely on GPS, the accurate DR available aboard a large ship with a gyrocompass, an accurate shaft tachometer or revolution counter, and the relative luxury of a large chart table and good plotting instruments. The surge in interest in celestial navigation comes not from those who are forced to learn it in order to qualify for a license, but from those to whom it is an important part of long-distance sail voyaging. The Marion to Bermuda sail race is notable in responding to navigators who enjoy using celestial navigation. The race includes a time penalty for using electronic aids to navigation systems.

Some learn merely to earn a certificate, perhaps good for bragging rights at the yacht club bar. Some of the courses seem deliberately complex, which may be appropriate to a certificate that is difficult to earn. But there is a new type of course developing, one that uses visual aids and simplified sight reduction methods to show ordinary yachtsmen that celestial is not incredibly difficult. These new courses are designed to introduce people to the art of celestial navigation with the essentials, rather than the formula derivations and multiple sight reduction methods so dear to many teachers.

The courses are responding to a market, a market of people who take, or plan to take, long sea voyages. These people want to be able to find their way in the event of an electronic failure; they may be fascinated with

the modern version of our ancient art; they may want to navigate in a highly traditional manner despite living in a complex and technically advanced world. A brief review of the market reveals that for an increasing number of people, celestial navigation fills those needs, and the *Nautical Almanac* helps to do so.

SUPPLIERS NOTED IN THIS PAPER:

Celestaire
416 S. Pershing
Wichita, KS USA 67218
(316) 686-9785
IN USA: 1-800-727-9785
Fax: (316) 686-8926
<http://www.celestaire.com>

Landfall Navigation
354 West Putnam Ave.
Greenwich, CT 06830
(203) 661-3176
Orders: 800-941-2219
Fax: (203) 661-9613
<http://www.landfallnav.com>

Starpath School of Navigation
311 Fulton St.
Seattle, WA 98109
800 995-8328
www.starpath.com



**Celestial Navigation
and
The Air Almanac
in the
KC-135R Stratotanker**



Lt Col Ed Sienkiewicz



Emblems shown

- upper left corner (Air Mobility Command)
 - our USAF parent Major Command (MAJCOM)
- upper right corner (19th Air Refueling Group)
 - my unit located at Robins AFB, GA
- bottom center (US Air Force emblem)



KC-135R Stratotanker from Grand Forks AFB, ND, refueling F-16 fighters from Cannon AFB, NM, somewhere in the world

Note that the newest KC-135 was built in 1964 (they were built from 1955 to 1964), making the tanker at least 35 years old



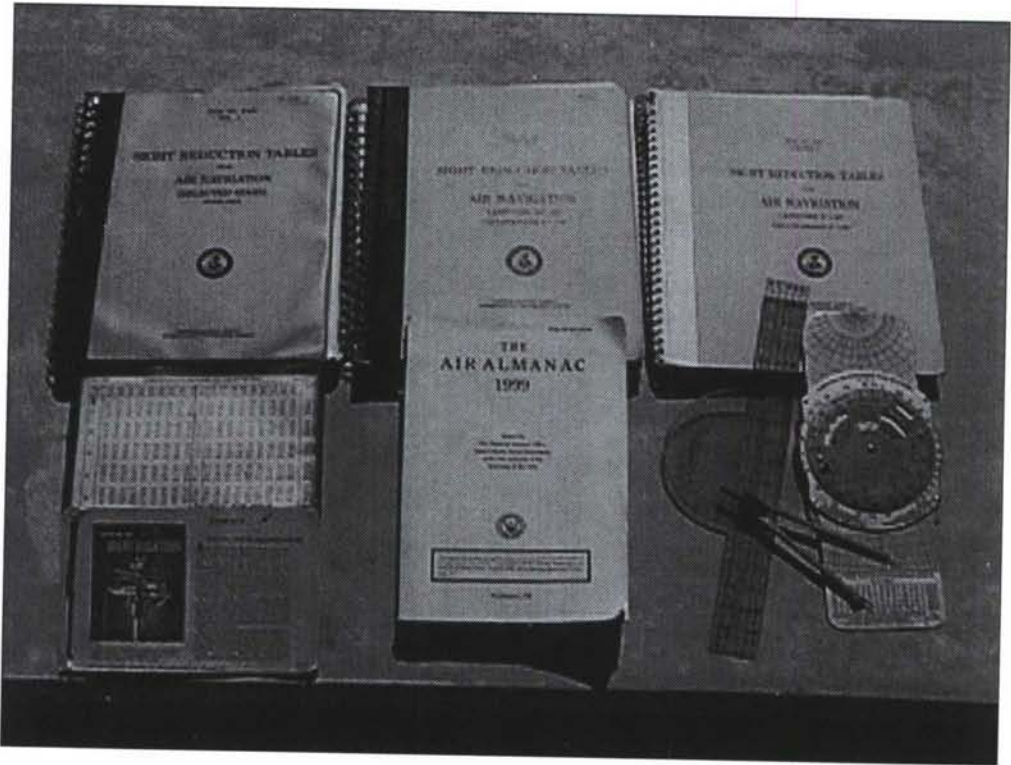
Looking forward into the cockpit of the KC-135, which houses the normal four person flight crew

The pilot sits front left, the copilot sits front right, the navigator sits behind the copilot (and faces towards the right side of the aircraft), and the boom operator would sit at his/her forward station to the rear left (just out of the photo)



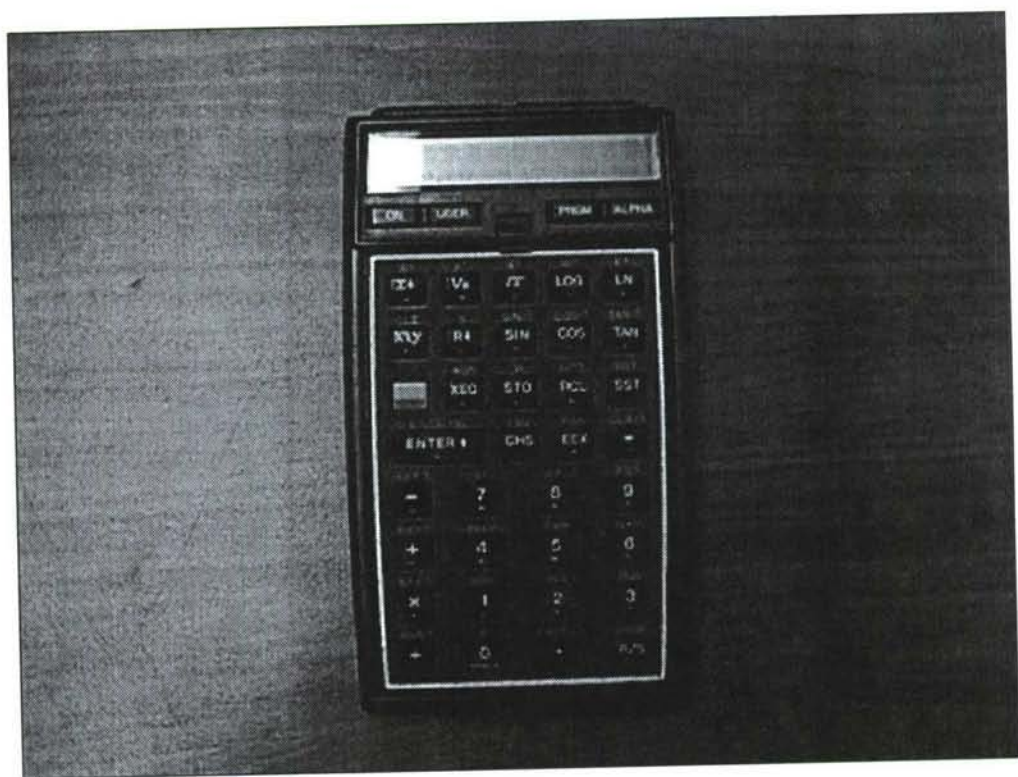
The tanker navigator hard at work at his position

Note the handheld Global Positioning System (GPS) unit to the far right on the nav table and *The Air Almanac* to the nav's left



The KC-135 navigator's tools for shooting celestial

- (Top) the three volume set of Sight Reduction Tables
 - contains data used in the celestial body sight reduction process
 - yields the body's true azimuth and computed altitude to locate the body in the sky
- (Middle lower left) a Coriolis/rhumb line correction chart
 - used to correct for the earth's Coriolis force and rhumb line error
- (Bottom lower left) a set of star identification tables
 - used to help find specific stars
- (Lower right) the nav's plotter, dividers, and handheld DR (dead reckoning) computer {"whizwheel"}
- (Lower center) *The Air Almanac*



My own HP-41C calculator which I've programmed (with formulas developed from the Naval Observatory's no-longer-published "Almanac for Computers") to do the bulk of the work of sight reduction

The celestial precomputation form we use to perform both our preparatory work for shooting a celestial body and, once we've taken our shots, to record the sights taken and then resolve our position

Note that this precomp form reflects a nighttime three star fix (with Polaris as a back-up) shot as we were tracking due east at 420 knots groundspeed (7 miles per minute) at 33,000 feet altitude virtually right over Washington, D.C.

The time of the fix was 0200 Zulu (2100 EST) on 5 March 1999

Note, too, that I've had to apply some adjustment to the sights to account for our movement over the earth (and the stars' movement in the heavens) during each shot

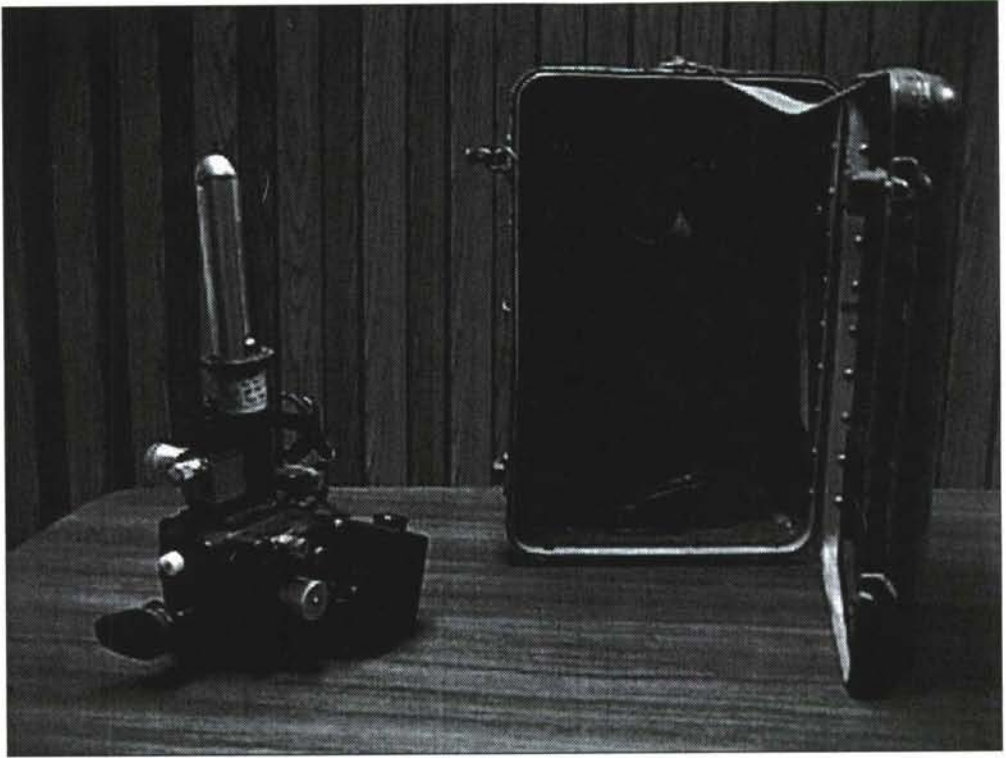


Photo of our periscopic sextant and its protective case used to secure it inside the aircraft

Note that this sextant costs about \$1300 to \$1400

Also note the sextant's eyecup at the lower left - this is where the navigator looks into the sextant



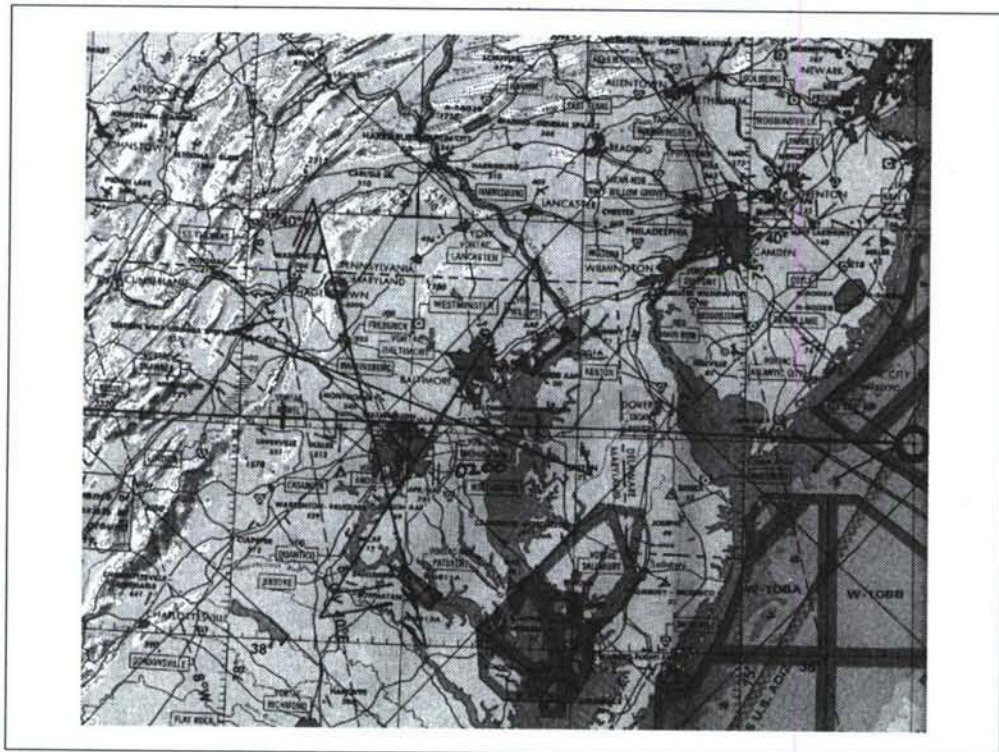
Another photo of the sextant (from the other side) showing the sextant's small observation window (at the top) that protrudes from the aircraft once the sextant is plugged into its sextant mount in the roof of the cockpit



Looking from the front of the cockpit toward the rear of the aircraft

The navigator is using the periscopic sextant to observe a celestial body

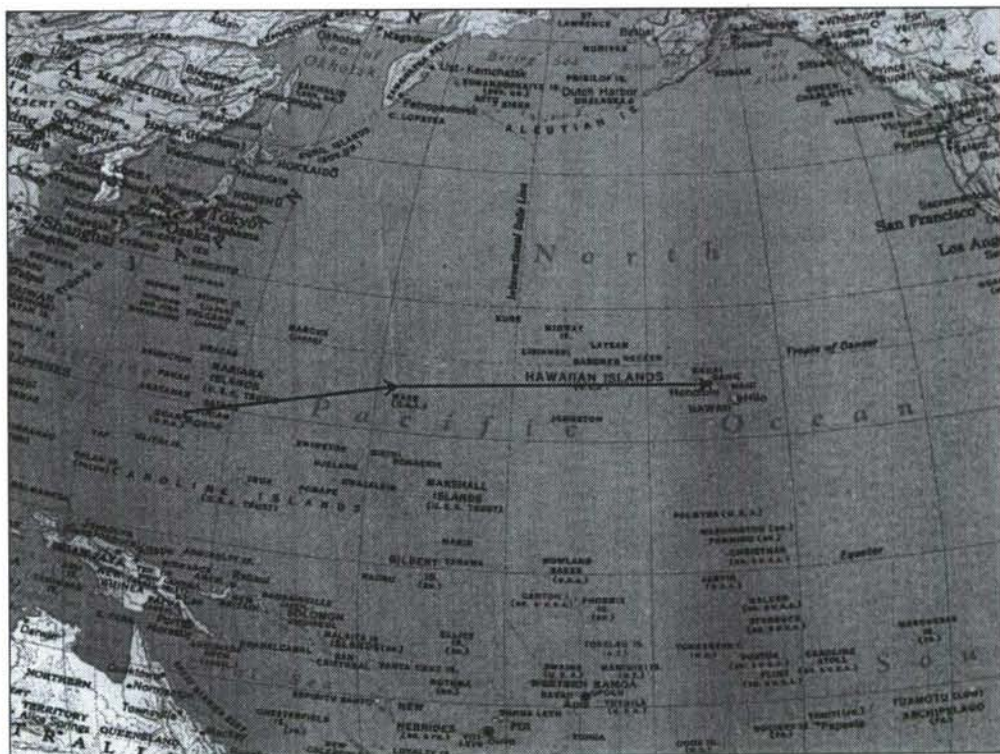
Note the white GPS antenna just behind the nav's head. It shares the sextant mount with the sextant



The resolved three star fix plotted over Washington, D.C.

Note the following:

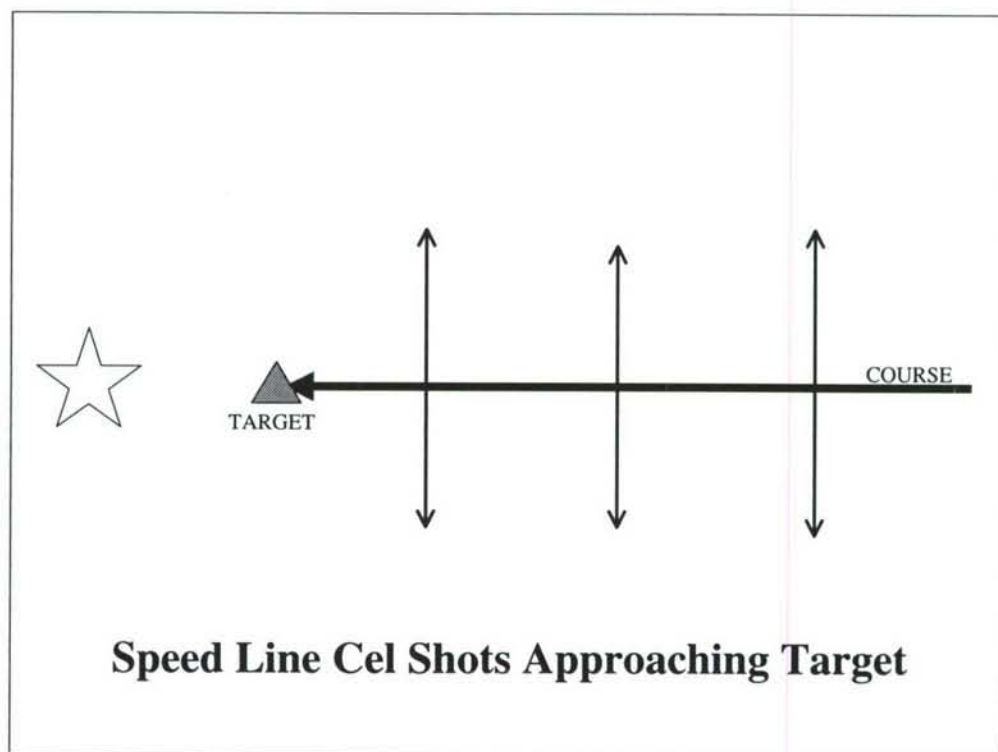
- the aircraft moved 70 nautical miles during the 10 minutes of celestial observation of the three bodies (see the two tick marks on the course line)
- the upside-down “v” symbol is where the assumed position was adjusted for Coriolis/rhumb line effect
- the small triangle (representing the fix) is not quite at the center of the larger triangle because the fix had to be adjusted for precession and nutation of the earth [based upon the fact that the star Sight Reduction volume was from epoch 1995 (over fours ago)]



War Story # 1 - my December 1977 eight hour night mission from Guam to Hawaii (via Wake Island)

- we were returning from a Pacific Tanker Task Force deployment
- our vintage 1956 aircraft did not yet have an inertial navigation system (INS) but it did have a very shaky Doppler system that provided marginal groundspeed and wind drift readouts
- me and the boom operator were shooting three star fixes about every 50 minutes for 3 hours from Guam to Wake Island and 4 more hours from Wake Island to Hawaii
- as we approached Wake Island, it was dead off the nose
- my proudest navigator moment

{reminded me of the 1943 Howard Hawks-directed WWII movie "Air Force" about a B-17 crew flying from Hawaii to Wake Island (and on to the Philippines) just after the Japanese attack on Pearl Harbor in December 1941}

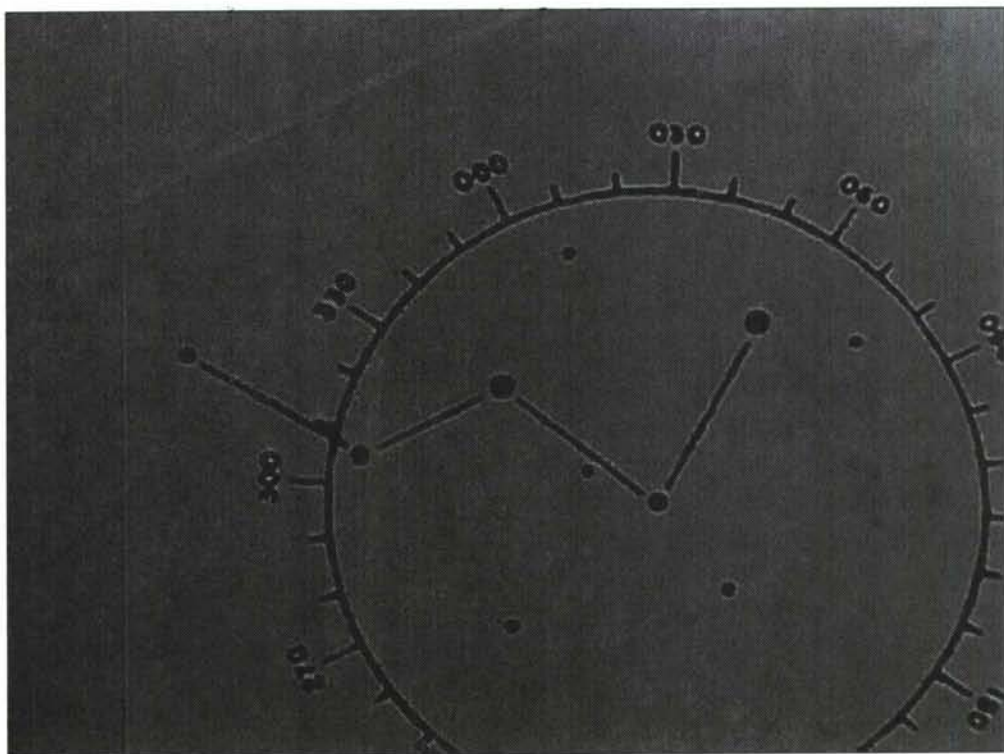


War Story # 2 - Strategic Air Command's (SAC's) Bombing and Navigation Competitions 1979 and 1980

- our 509th Bomb Wing planners used *The Air Almanac's* star data pages to select a perfect speed line star as we would be approaching our celestial navigation leg's termination point

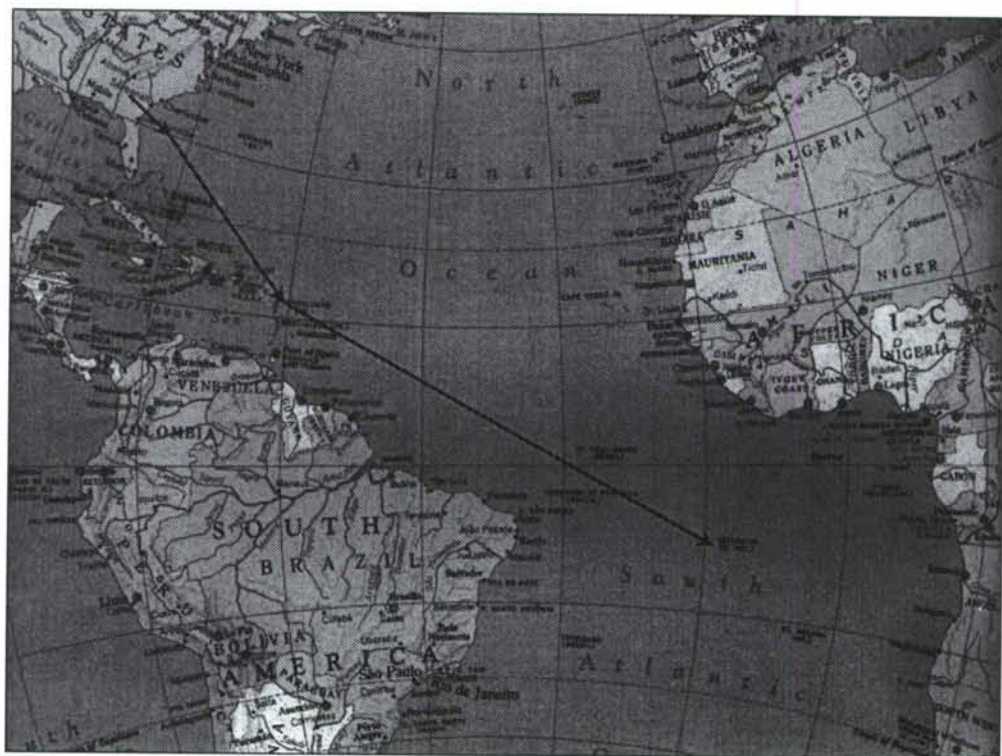
- we would use the star shots to gauge our final run into the target

- the diagram represents the following: the course into the target; a celestial body directly off the nose (or tail) of the aircraft - which would yield an exact speed line LOP (line of position); and the actual speed lines themselves (the lines with arrowheads at both ends)



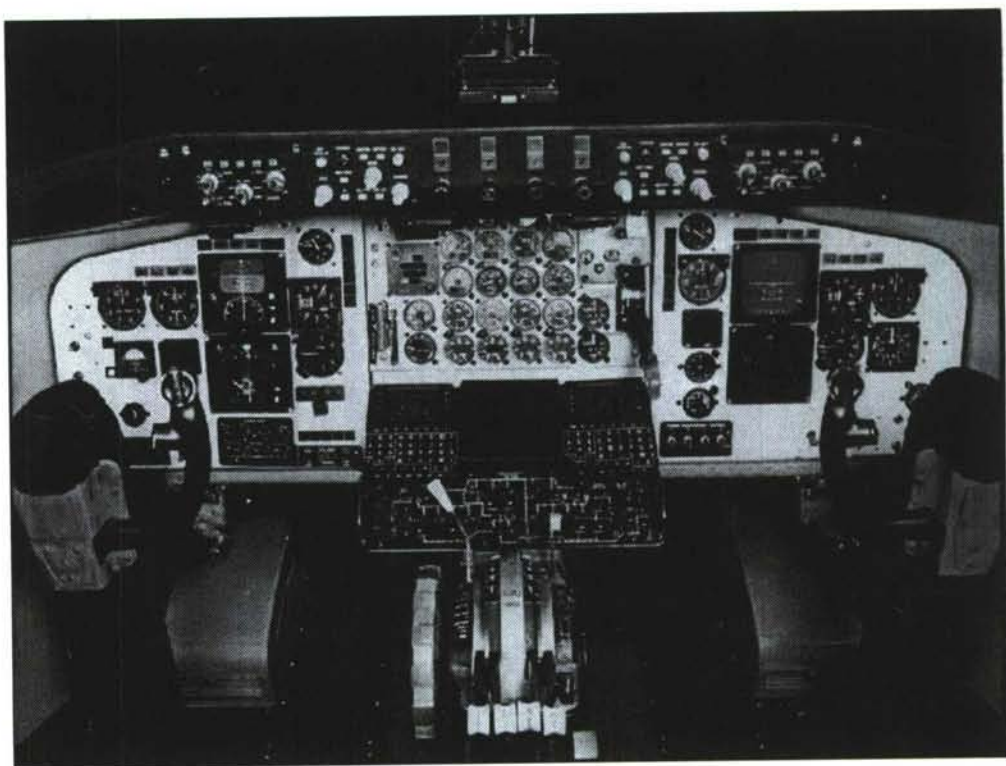
A close-up of a star diagram we actually used to find that perfect speed line LOP

- the diagram shows the Chair of Cassiopeia with the star Schedar in the middle of the circle
- we used the star Ruchbah (delta Cass), just inside the circle at the 300 degree mark of the circle
- techniques like this helped our 509th Bomb Wing win SAC's coveted Fairchild Trophy as the best Bomb Wing in 1979 and helped both of our wing's two tanker crews (my crew included) place in the top 10 (of about 70 crews) in the 1980 competition



War Story # 3 (cut to the present day) - February 1998

- our 19 ARG was supporting President Clinton's trip to Africa by flying 10 hour support missions from Robins AFB, GA, to tiny Ascension Island in the South Atlantic
- on this mission the crew lost its GPS antenna (bad connection) and had only a single INS
- once leaving the Caribbean SE-bound the two person nav team spent the next 6 hours shooting 3-star fixes
- as they approached Ascension Island the crew determined that its actual position was within 5 nautical miles (NM) of where the nav team had it plotted
- quite a navigation feat !



But now as we approach the beginning of the 21st century, the bell tolls for the end of celestial navigation in the KC-135, and quite possibly the end of the navigator in the aircraft, too

This is a photo of the KC-135 Pacer CRAG (Compass, Radar, and GPS) “glass” cockpit showing the greatly improved avionics at the pilot’s and copilot’s stations

The now three-person crew (minus the navigator) with the enhanced aircraft avionics is already flying operational missions as the new system is going through its final proof-of-concept testing



Note, though, that the USAF's RC-135 aircraft (shown here) will continue to employ celestial navigation (and the navigator) at least until the year 2010



19th Air Refueling Group “Black Knights” - note our knight’s head on the upper part of the aircraft’s vertical stabilizer

- when this photo was taken, this KC-135R belonged to the 19th

HOW ASTRONOMERS USE *THE ASTRONOMICAL ALMANAC*

Heidi B. Hammel
Massachusetts Institute of Technology

Introduction

In astronomy, there are as many uses for *The Astronomical Almanac* (hereafter AA) as there are astronomers. As I was preparing this paper, I thought about my own use of the AA during the past year, and was surprised to find out that I'd thumbed through more than two thirds of the sections in the past few months. Thinking back over the past few years, that percentage rose to over 90% of the book! My assessment is remarkably similar to that of my colleague Wayne Osborn:

Just recently, but also about 15 years ago, the USNO asked readers of the AA to indicate what sections they used. I went through the book page by page and was amazed to find that over the years I had made use of almost every section at one time or another.¹

An informal query² of members of the American Astronomical Society resulted in usage descriptions that spanned the whole of the contents of the AA. In broad terms, the astronomical uses of the AA can be categorized into five main areas. These are: (1) planning observations before going to a telescope; (2) navigating around the sky once one is at a telescope; (3) performing analyses of astronomical data after observations have ended; (4) providing astronomers with fiscal opportunities or preventing financial disasters; and (5) inspiration. I discuss each of these areas in more detail below, providing examples when applicable.

Planning Observations

When an astronomer is preparing to use a telescope, she or he needs to know many things. First and foremost, the astronomer usually will want to observe when the target object is highest in the sky and visible for the longest time (one exception is time-critical observations, for example planetary occultations or binary star eclipses).

Once the optimal observation time has been established, a multitude of other considerations comes into play. Where is the Sun in

relation to the target object? (Often the observations are best when the Sun is opposite the object in the sky.) When will the Sun rise and set at the observatory, or, often more important, when is the sun comfortably far enough below the horizon to not interfere with sensitive measurements of brightness? (Most frequently used for astronomy is "astronomical twilight," when the sun is more than 12° below the horizon.) Where is the Moon in relation to the object, when is lunar rise and set, and what is the lunar phase? The AA addresses these issues.

Some astronomers also use the AA's object-specific tabulations for planning their observations. These may include the locations of the planets and the brightest asteroids, and the positions of planetary satellites relative to their parent body. Also of relevance are the timing of various phenomena such as eclipses and transits.

Many astronomers now run various software packages to determine such things. However, equally many (I included) find it often easier to simply reach out and pick up our hardcopy of the AA. After a few months, the book will often fall open to the pertinent pages, and the relevant page numbers have usually been committed to memory after years of use.

Sky Navigation

I've found the AA at every professional observatory I've ever been to; sometimes it is in the control room, sometimes it is out at the telescope itself, and sometimes there are multiple copies scattered around for easy access. The most frequent at-telescope use by professional astronomers is to verify the pointing of the telescope by using either the Moon or the list of bright stars (more on that list later, though!).

Some astronomers also use the AA at the telescope to look up satellite positions. For example, I have used the AA to verify the orientation of the telescope field of view by comparing tabulated relative positions of satellites with observed positions in an image.

Here is a different example of the AA's use in real time. In 1994, the fragments of the shattered comet Shoemaker-Levy 9 crashed into the planet Jupiter. Prior to the event, no one knew for sure whether the collisions would produce phenomena detectable from Earth. Nevertheless, the potential was high enough that virtually all facilities were mustered. As leader of a team of scientists using the Hubble Space Telescope to observe the collisions, I scheduled a series of observations for the time when the first fragment was predicted to hit the atmosphere. We gathered

in the basement control room at the Space Telescope Science Institute to watch with breathless anticipation as our first image appeared on the screen. Down on the lower left side of Jupiter was a small bright spot. "What's that?" called someone. Being a skeptical observer, I replied, "It looks like a satellite coming out from behind Jupiter. Where's the AA? Somebody check!" Within seconds, the AA had materialized and several people scrambled to the pages for Jupiter's satellite reappearances. A moment later the next image appeared, and it was clear that the small odd protuberance was not a satellite, but rather a plume of material ejected some 3000 km above the cloud-tops of Jupiter.³

Astronomers also reported using the AA as a tool for teaching the fundamentals of observational astronomy. For example, Wayne Osborn reports, "We have used the AA as a 'textbook' in our observational techniques class for the past twenty years. We teach the students how precession, sidereal time, apparent positions, etc. are computed and how to determine the local circumstances of eclipses, exact times of sunrise and sunset, the moon's position, etc."⁴ Finding the moon and planets were also cited by other teachers of astronomy. Dave Pierce writes:

In my community college astronomy classes I require students to observe the Moon during a complete phase cycle. I use the moonrise/moonset part of the AA to identify bogus observations allegedly made when the Moon isn't up. I also use the Planetary Phenomena tables for monthly reports on what's up in the skies.⁵

E. Myles Standish shares the following unexpected classroom observation (note: "Blue Book" is astronomers' affectionate name for the AA):

A Blue Book story from my very first astronomy class at Wesleyan, too many years ago: Professor Carl Stearns was showing us that one could see Venus in the daytime. So he took us to the 20" refractor, looked up the coordinates in the AA, and showed us how to point the telescope. All of a sudden there was a giant bright spot threatening to burn a hole right through the opposite wall of the dome. "Yikes!" He jumped across the floor and picked up the Blue Book. "Oops, I guess I looked up the sun by mistake."⁶

People who do public outreach in astronomy report using the AA at the telescope for reasons similar to those of professionals: looking up

the position and phase of the Moon; and finding planets and identifying satellites. Martin Ratcliffe describes an additional use of the AA for non-professional astronomers:

I use the AA for the monthly column I write in *Astronomy* magazine (the Monthly Sky notes section). [It is my] primary source of information on positions and magnitudes of solar system objects, and occasionally for other data. The phenomena of the year that would be of interest to the amateur astronomer (conjunctions, elongations, eclipses) are also used extensively.

Since my column is written at least five and sometimes six months ahead, for about four months of the year the AA is my only reliable source of information (other sources are published around November of each year, but by then I have already written my January-April columns).

Last year I also wrote the annual guide to the night sky for *Astronomy* called "Explore the Universe 1999." I plan to be working on the 2000 issue very soon, and will use the AA extensively.⁷

The readership of *Astronomy* is about 245,000 people (185,000 subscriptions and 60,000 newsstand sales); thus the impact of the AA extends far beyond those who get actual copies of the book itself.

Data Analyses

Most professional astronomers spend only a limited amount of time actually at a telescope, and that time is spent solely on getting photons "down the tube" and safely recorded on a computer. Far more time is spent back at their offices analyzing the data. The AA frequently plays a critical role in this aspect of professional astronomy.

The number of uses of the AA for data analysis is, well, astronomical. Here are just a few examples. I recently used the AA to double-check a computer code that calculated planetary positions and Earth-planet distances. I also looked up physical parameters about planets and satellites for an article in preparation, and updated a computer program with extremely precise time-scale conversion factors.

Several researchers cited the section focussed on the Sun. Amy J. Lovell writes, "We use the AA to get the solar position and distance, among other things. This is important for thermal models of asteroids,

because the sub-solar position (and a very accurate solar distance) is crucial to the understanding of the heat transfer [in the asteroid's surface]."⁸

In a phone call, Joseph Hirman described the critical role that the AA plays in space weather monitoring.⁹ He and his colleagues use not only the more obvious parameters such as the sunrise/sunset times and the apparent solar positions, but they also rely heavily on the solar position angles and the heliographic latitudes and longitudes.

For some aspects of data analysis, the longevity of the AA can provide a critical context for long-term phenomena. Chuck Higgins notes this underutilized aspect of the AA:

While a graduate student at the University of Florida (UF) my professors and I used the AA extensively in our observations and data analysis of jovian decametric radio emissions. The radio program began at UF in 1957... The AA helped all of us with calculating times of opposition, times of transit, the phases of the satellites, and most importantly, an accurate central meridian longitude (CML) of Jupiter. I was able to use nearly 40 years of decametric observations from UF to calculate a new and more precise rotation period of Jupiter.^{10,11}

Financial Gain ... or Loss!

A surprising number of legal decisions seem to hinge on the location of the Moon. Many astronomers have stories to tell, enough so that one astronomy teacher mentioned lawyers explicitly when justifying using the AA to calculate specific astronomical event times.¹²

I experienced a typical "astro-legal" experience in graduate school. A lawyer for an insurance agency contacted me: a man had claimed that he wasn't responsible for an automobile accident in which he drove his car off the road because the full moon blinded him and he didn't see the road curving. Using the AA, I determined that while the moon was full that night, it wasn't where the man had alleged at the time of the accident.

I suspect the AA will continue to be used in this capacity in spite of the plethora of easily-obtainable astronomical software. In a court of law, an attorney needs to cite a specific document as a resource. The difference between "according to the figures published by the U.S. Government Printing Office, I can show that..." and "I ran a program on my PC last night and it said..." could make or break a case. (The need for

astronomical legal counsel apparently persists: one participant in the NAO Symposium came up after my talk to discuss rates, since he was thinking of going into the consultation business on the side.)

A completely different twist on the use of the AA in a business setting is revealed in the following story related by Wayne Osborn, where the potential for financial *loss* by using the AA was narrowly averted:

At the end of 1996, we replaced our old Celestron-14 in the campus observatory with a computer-controlled 16-inch reflector by D--. The D-- technician came and installed it and it was working well in a few days. However, a little while after he left we had a problem with one of the control boards, and D-- ended up shipping a replacement. Then it was semester final exams and Christmas vacation.

The first clear night in January 1997, I took a few people to the observatory to show off the new telescope. After explaining that the new telescope wasn't much larger than the old one but much more convenient with computerized pointing, I pointed at a bright star. The display gave coordinates miles off from those listed in the AA! I re-set the telescope coordinates to those in the AA and tried to find M31. It wasn't there! I rechecked the coordinates and found no errors. Obviously, my demo of our new telescope was a disaster and I was convinced that there was an error in the D-- pointing code.

We have such faith in the AA that it never occurred to me that the listed AA star coordinates could be wrong. But in the 1997 AA, somehow the list of bright stars had 1968 coordinates (listed as 1997.5) by mistake. Just as I was about to give D-- an earful, I saw a notice about the AA error, and ended up warning the D-- technician about it. He was very thankful as he always uses the AA to align and test a telescope and he was just leaving for Japan for his first installation of 1997!¹³

Inspiration

Because the use of the AA is so entwined with the practice of modern astronomy, it comes as no surprise that many astronomers have intensely personal stories to tell about its effect on their lives and their choices. Richard Binzel writes:

December 1, 1970 was the first time I ever saw Saturn through a telescope -- the singular experience that led me to want to study the solar system, as opposed to black holes. I have been looking forward to the day when Saturn returns to the exact same location in the sky to celebrate the first of the two Saturnian years I hope to recognize in my lifetime. It is the archival 1970 American Ephemeris and the 1999 Astronomical Almanac that let me pinpoint the date for the first anniversary.¹⁴

The contents of the AA and its Explanatory Supplement are a boon to practicing astronomers. Chuck Higgins speaks for many astronomers when he says, "Without the AA to guide me through some of the tedious calculations [needed for our project], I would not have made it."¹⁵ The work of the people who produce the AA makes the practice of astronomy more efficient and allows telescope time to be used more effectively. That leaves astronomers time to ponder the subtle intricacies of their data, rather than spending time mired in mundane mathematics.

Perhaps the most poetic inspiration ascribed to the AA comes from my colleague Nicholas Schneider:

I first encountered the AA as an undergraduate. Like most tabulations, it seemed at first to be useful but uninterpretable. I came to realize, though, that each section was just the embodiment of the geometry of the solar system. With Kepler, Newton, and Euclid you could put together the big picture. So section by section, column by column, I built up the mental model solar system that I still use today. (It wasn't all easy - especially things like the equation of time!) I credit the AA with introducing me to the beauty of the clockwork solar system, which has led to an enjoyable career in planetary science.¹⁶

As Schneider expresses, the AA is a tabular version of the elements in our Solar System and beyond. The sustained creation of this document is truly a marvelous and inspirational enterprise. On behalf of all astronomers who use *The Astronomical Almanac*, I express thanks and best wishes to the Nautical Almanac Office on this occasion of their Sesquicentennial.

NOTES

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5. Dave Pierce to HBH, 1/12/99, email.
6. E. Myles Standish to HBH, 1/11/99, email.
7. Martin Ratcliffe to HBH, 1/11/99, email.
8. Amy J. Lovell to HBH, 1/28/99, email.
9. Joseph Hirman to HBH, 1/28/99, telephone call.
10. Chuck Higgins to HBH, 1/28/99, email.
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12. Wayne Osborn, op. cit., email.
13. Wayne Osborn to HBH, 2/15/99, email.
14. Richard Binzel to HBH, 1/12/99, email.
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16. Nicholas Schneider to HBH, 1/11/99, email.

INTERNATIONAL COOPERATION

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Abstract

There is a history of international cooperation involving the Nautical Almanac Office for over one hundred years. This cooperation has involved standardization of constants, theories, definitions, methods, and publications. There has been a continuing cycle of improvements in standards, which have led to more accurate theories and observations, which have in turn required more improvements in standards. Thus, the years have seen continuing technology and accuracy improvements. There has also been an increasing level of excellence and efficiency through this cooperation.

Through this period, incorporating the effects of general relativity has become a continuing challenge, as increased accuracies have required more rigorous and complex formulations. With the limited overall understanding of general relativity, the international acceptance and adoption of relativistic standards has been and continues to be challenging.

Portions of this paper are reminiscences of personal involvement. All international cooperation involves people and their organizations. Both have changed over the years, but the successes of cooperation have largely been due to the spirit, intelligence, and friendliness of the individuals from the many countries. This has led to many friendships and special memories over the years.

Early Cooperation

International cooperation among the organizations preparing almanacs began with the International Meridian Conference in Washington in October 1884¹. At this conference the Greenwich meridian was adopted as the standard zero meridian. It was also agreed that east longitudes would be positive and west negative. Probably for psychological reasons, the letter W was used instead of a negative sign until the 1981 publication of *The Astronomical Almanac*. It was also agreed that astronomical and nautical days would begin at midnight.

The next step was the Conference International des Etoiles Fundamentals in Paris in May 1896. At this conference, standards for fundamental catalogs and apparent places of stars were established and standard values of constants were adopted for nutation, aberration, solar parallax, and Newcomb's constant of precession, although the actual value was not yet available¹.

In October 1911 in Paris, the Congress International des Ephemerides Astronomiques developed the plan for cooperation between national almanac offices, and increased the list of apparent places of stars. The standards for calculations were specified and the work distributed among the five principal offices in France, Germany, Great Britain, Spain, and United States. Additionally, standard values for the flattening of the Earth and the semidiameter of the Sun were adopted. Congressional approval was received in 1912 for the exchange of data and the repeal of the requirement to use the Washington meridian¹.

The International Astronomical Union was founded in 1919, and IAU Commission 4, Ephemerides, encouraged cooperation among the almanac offices and preparation of ephemerides. Commission 4 is the lowest numbered commission still in existence. In 1938, Commission 4 recommended avoiding duplication of publications. In 1941, the Fundamentalkatalog (FK3) was implemented and the publication *Apparent Places of Fundamental Stars* introduced. An indication of the level of cooperation and seriousness of the exchange of data at this time is the fact that by a decision at the highest level, the Nautical Almanac data were provided by the U. S. to the Germans through the embassies in Sweden throughout World War II.

The 1950's and 1960's

At a conference in Paris in March 1950, Ephemeris Time was defined, bringing the lunar and solar ephemerides into accord. No changes to any constants were adopted at this conference. At the IAU General Assembly in 1955 in Dublin, a general redistribution of calculations was developed based on the availability of calculating machines and the efficiency of all calculations of a given type being done at one place. In July 1955, the atomic time scale was begun and this would significantly effect the availability and definitions of time scales in the future. Almost twenty years after the recommendation to avoid duplication of publications, the only publications to be discontinued, German Jahrbuchs, ceased publication in 1957 and 1959¹.

The navigational almanacs of Great Britain and the U. S. were unified for 1960 and reproducible material was made available from Great Britain. The first *Explanatory Supplement*, a joint publication by the U.S. and British Nautical Almanac Offices, was published in 1961¹. At the 1964 IAU General Assembly in Hamburg the IAU System of Astronomical Constants was adopted for introduction in 1968. The changes were detailed in an Appendix to the *Explanatory Supplement* and *Supplement to the AE* in 1968.

Time for Changes, 1970's

In 1970, before the IAU General Assembly, there was a meeting in Heidelberg, Germany to plan the needed changes, recognize the need to include general relativity, and establish working groups to decide on recommendations. Resolutions were drafted at a meeting in Washington in 1975.

At the IAU General Assembly in Grenoble in 1976², resolutions were adopted for changes to be introduced in 1984. These changes made order of magnitude improvements in accuracy for ephemerides, time scales, astronomical constants including precession and nutation, star catalogs, and the equinox. After I returned from Grenoble, Charles Misner called to tell me that we had not included relativity for the constants. Upon discussion, he said the effect was just beyond the significant figures the IAU had adopted, a precursor of future relativistic requirements.

The new system required a paper to give a new definition of UT1. Two groups, USNO and Japanese, were drafting such papers and a joint paper including authors from two other countries resulted. An astronomer whose name started with "A", suggested the authors be listed in alphabetical order. After a continuous series of revisions to the English in the paper by a foreign co-author, I sent the paper to the publisher and informed the co-author, thus bringing an end to the rewriting³.

In 1979, the Nutation Working Group, of which I was chairman (because I did not attend a meeting in Kiev and protect myself), could not get an IUGG decision on an Earth model. Since the choice was insignificant to the nutation theory, a well-known model was referenced. This led to a request from the IUGG to revise the recommendation and achieve agreement by the working group in Warsaw in 1980⁴.

Walter Fricke kept delaying the decision concerning the correction for the FK5 equinox and equinox motion. Finally, facing a publication deadline, I sent Walter a letter saying that we were adopting the values in

his latest publication and referencing it. To ensure continuing good relations and to make peace with Walter, I added a weekend visit to Heidelberg in a multistop trip to Europe. I arrived concerned about his reaction, but he greeted me with the statement that his colleagues told him he should appreciate what I did and now he could get on to other things. Then, he proceeded to carry on a continuous, but pleasant, series of scientific discussions during every waking hour of the weekend.

As part of the new arrangements, a single publication would continue *The American Ephemeris and Nautical Almanac* and *The Astronomical Ephemeris* in 1981. The compromise title *The Astronomical Almanac* was agreed upon, but this required congressional action, since the old title was in the U.S. Code. As a single action, there would be difficulty generating any enthusiasm for such an act in Congress. Fortunately, at this time, the USS Wyoming was being decommissioned and the state of Wyoming wanted the silver service for a museum there. The two actions were combined and two senators and one representative of Wyoming supported the name change to *The Astronomical Almanac*. Thus, the book was renamed and completely reformed in 1981 based on many discussions between George Wilkins and me, as the directors of the British and American Nautical Almanac Offices. In 1984, the many scientific changes agreed upon by the IAU were introduced².

Post 1984

The expected effects of the changes introduced in 1984 were almost immediate. The known errors were eliminated, and now discrepancies an order of magnitude, or more, smaller were detected, and new corrections could be investigated.

There were a number of concerns about the new time scales, with significant disagreements between the metrology community of timekeepers and the astronomical community. At an IAU Symposium in Coolfont, West Virginia, Bernard Guinot and I took a walk in the woods to discuss the disagreements and this resulted in a joint paper⁵ that would lead to new resolutions adopted in 1991 at the IAU General Assembly in Buenos Aires.

The VLBI observations were making possible a new extragalactic reference frame with milliarcsecond accuracy based on radio sources. In October 1990, an IAU Colloquium was held at Virginia Beach to develop resolutions to adopt a new reference frame, a relativistic gravitational

potential, and new time scales. These were adopted at the 1991 IAU General Assembly².

In 1992, a new revision of the *Explanatory Supplement*⁶ appeared based on all the changes adopted since 1961.

After the 1991 IAU General Assembly had adopted the new time scales, I was asked by several people to write another paper explaining the new time scales. Since Bernard Guinot did not wish to co-author the paper and Toshio Fukushima had developed part of a paper, we combined to write a paper⁷. Once we had a version submitted for publication, Toshio decided to distribute the paper by e-mail, the first paper so distributed. I, at least, was surprised by the reaction. People assumed the paper must be important, read it immediately, and sent comments and questions within 24 hours. We were obligated to respond with equal rapidity.

The Hipparcos astrometric satellite has produced an optical reference frame at the milliarcsecond level, which has been made consistent with the fundamental extragalactic reference frame. Now astrometry was clearly at the milliarcsecond level. In addition, charge coupled devices had replaced photographic plates as the optical detectors and improved the ground-based observations by an order of magnitude.

The Present

There has been a change from the dynamical reference system to a kinematic system. As a result, the origin is arbitrary and there is a need to clarify the definitions and relationships between the different reference frames. The observational determination of nutation is more accurate than the theoretical representation, and the non-rigid Earth models cannot satisfy the most accurate observational data. Thus, weekly observational determinations are required for the highest accuracy.

There is the old issue of the use of standard values over a period of time or the more frequent changes to the use of currently best values. Now, however, there is more rapidity in the changes and availability of best values.

Relativity continues to be an issue requiring development of new standards to achieve the improved accuracies. There are two IAU working groups currently trying to develop standards for metrology, gauges, metrics, time scales, celestial mechanics, geodesy, and astrometry.

The Global Positioning System (GPS) has provided a new capability for accurate navigation and largely supplanted all other methods. Now there is concern about the availability of a backup system. Celestial

navigation may have a new importance as the only available backup system. GPS has made accurate time available worldwide continuously at the nanoseconds level. The U.S. Naval Observatory realization of Coordinated Universal Time is the basis of GPS time. In addition, observations of the GPS satellites provide a continuous source of the most accurate polar motion data, and motions with periods less than a day can be seen. UT can also be determined from GPS observations for intervals between VLBI observations of extragalactic sources. Thus, the GPS observations can provide interpolations between the more fundamental VLBI observations.

Having progressed to the milliarcsecond level in the past decade, astrometry is now about to move to the microarcseconds level. There are proposals and projects for astrometric satellites such as FAME, SIM, DIVA, and GAIA. These satellites will observe in the 1-500 microarcsecond level and require methods, constants, and theories at the submicroarcsecond level. International cooperation is already in progress to develop and recommend these new standards.

Institutions and People

In practice, international cooperation is achieved through people and organizations. There has been a mixture of stability and change over the years, and the people of course change as careers begin and end. Unfortunately, organizations have also experienced limited lifetimes in some cases. In the last half century The Royal Greenwich Observatory has moved from Greenwich to Herstmonceux to Cambridge to oblivion. Her Majesty's Nautical Almanac Office (HMNAO) survives at Rutherford Appleton Laboratories. The Institute of Theoretical Astronomy has been abolished, but portions of it have continued at the Institute of Applied Astronomy and Pulkova Observatory, all in St. Petersburg, Russia. The Bureau des Longitude has changed name and status and became the Institute of Celestial Mechanics and of Calculation of Ephemerides (IMCCE) in Paris.

During my career the superintendents of HMNAO in England have been D. E. Sadler, G. A. Wilkins, B. D. Yallop, A. T. Sinclair and P. Wallace. In Germany the directors of the Astronomisches Rechen Institut have been W. Fricke and R. Wielen. In France the heads of the BDL have been J. Kovalevsky, B. Morando, J. Chapront and J. E. Arlot. In Russia the institute directors involved have been V. Abalakin, A. Sokolsky, and A. Finkelstein. In the United States the personnel have included W.

Eckert, P. Herget, G. Clemence, E. Woolard, and R. Duncombe. R. Haupt, B. Morrison, L. Doggett, P. Janiczek, J. Bangert, and A. Fiala have accomplished the publications of the NAO. There have been many more people than I can name here involved in this cooperation, and I have enjoyed being a part of the international cooperation over the last thirty years, both in what has been accomplished and the many friendships developed.

NOTES

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NAVIGATION AND PRECISE TIME

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Precise time has traditionally been associated with navigation and this association continues to grow today. From celestial navigation to the Global Positioning System (GPS), precise time is an essential component in obtaining a precise location. The accuracy of navigation is directly related to our ability to keep precise time. As we go forward, the navigational requirement will continue to drive attempts to improve timing precision and to make precise time available to the user.

Introduction

The role of precise time in navigation stems from two metrics. In the use of celestial navigation, the error in longitude positioning caused by an error in time of one second is one quarter of a mile at the equator. This is due to the distance moved by a site on the Earth caused by the Earth's rotation. Electronic navigation, which makes use of the known speed of propagation of electromagnetic radiation, will suffer an error in positioning of one meter for each three-nanosecond (ns) timing error.

Celestial Navigation

The concept of celestial navigation is to measure the altitude of celestial bodies by some optical means and note the time at which the observation is made. Observations are then reduced to solve for the position on the Earth where the celestial bodies would have those altitudes at the time of observation. Typical accuracy achieved using celestial navigation is approximately one nautical mile. Celestial navigators are generally happy to have time to one second.

The need for precise time for celestial navigation is clearly demonstrated by the story of the British Admiralty's eighteenth century search for a means to achieve accurate time at sea. Harrison's long search for a precise time-keeping device for ships is well known (e.g., Sobel 1998) and testifies to the urgency of the timing requirement.

This concept has been extended recently with a proposal for automated celestial navigation (see Kaplan 1999, this volume). This method would update an inertial navigation system with optically observed directions to celestial bodies in a feedback loop. Accuracy of a few hundred meters might be expected. Anticipated timing requirements are at the level of milliseconds.

Electronic Navigation

Electronic navigation relies on the known distance traveled by electromagnetic radiation. This means that the accuracy of the method is directly related to accuracy of the timing in the navigational system. On the other hand, we now see that, because precise timing is critical to electronic navigation systems, the navigation systems have become some of the most important means to provide time to the non-navigational time users. Navigation systems have become time dissemination systems. The current major electronic systems for navigation include Loran-C, the Global Positioning System (GPS), and GPS augmentations.

Loran-C uses electronic receivers to determine the difference in the time of arrival of signals from two Loran-C broadcasting sites. This allows the user to place his location on a hyperbolic path on the Earth's surface. Using similar information from another pair of Loran-C stations, the user identifies another hyperbolic path (Loran-C User Handbook). Where these two paths intersect is the navigator's position. Positional accuracy is approximately thirty meters, and the timing accuracy required to operate the system is 100 ns.

The well-known GPS operates by providing satellites that broadcast precise time and satellite ephemeris signals. The navigator uses a receiver that determines the apparent ranges to the observable satellites by transforming the difference between the satellite time and the receiver's time into distance using the speed of light. Observations of four satellites provides the navigator with a three dimensional position and a correction to his clock. The unauthorized user (one who does not have access to the precise code) may expect to achieve an accuracy of 100 meters in a horizontal dimension, 156 meters in the vertical and a

time accuracy of 200 ns. The authorized user who does have access to the precise code may expect an accuracy of 22 meters in the horizontal and 28 meters in the vertical directions along with time accuracy of 50 ns. In both cases the user may reduce these errors by averaging over a suitable time interval (Hurn, 1989). The U. S. Naval Observatory is required to monitor the satellite clocks with an accuracy of 12 ns to provide the accurate time critical to the operation of the system.

GPS augmentation systems seek to enhance the operation of the GPS by providing differential corrections to the GPS broadcast signals. These corrections are determined by using stations at known locations to monitor the GPS satellite to determine these corrections and provide, in some cases, information on the health of individual satellites. The most prominently mentioned of these systems include the Wide Area Augmentation System (WAAS), the Local Area Augmentation System (LAAS), and the Maritime Differential GPS. Typical accuracy is expected to be a few meters, and timing accuracy of a few tens of nanoseconds is anticipated (Enge *et al.*, 1996; Loh *et al.*, 1995)

Global Positioning System

The most prominent of navigational systems now in use is the GPS. It can furnish the user with their position, velocity and time. The GPS satellites provide GPS Time, a time scale formed by an ensemble of clocks at the GPS monitor sites and the clocks in the satellites themselves. It is steered to the U.S. Naval Observatory (USNO) Master Clock which is designated UTC(USNO) (modulo one second). The satellites also broadcast corrections to GPS Time to obtain Coordinated Universal Time as maintained at the USNO. This version of Coordinated Universal Time, designated UTC(GPS) is kept to within 28 ns of UTC(USNO). These timing signals have become the basis for comparison of laboratory clocks around the world, and they provide one of the most popular ways to receive timing information for thousands of military, commercial and scientific users. In practice, UTC(GPS) accuracy does not exceed the 28 ns tolerance. Figure 1 shows recent comparisons of UTC(GPS) with UTC(USNO).

The U. S. Naval Observatory (USNO) is tasked by the U. S. Department of Defense (DoD) to furnish overall management of the Precise Time and Time Interval (PTTI) program. This includes the operation of the Master Clock, dissemination of time to DoD users and providing synchronization and other time-related information. In this

capacity USNO provides the GPS observed data on the time differences between the satellite clocks and the Master Clock. It also maintains the USNO Alternate Master Clock (AMC) at Schriever Air Force Base (the Master Control Station of the GPS) which serves as the local clock for the Schriever Air Force Base GPS monitor station. The AMC clock then becomes the dominant timing source in the formation of GPS Time. Further, the USNO also provides Earth orientation information to the GPS so that the GPS orbits can be related to the terrestrial reference frame accurately.

The USNO time scale is produced from an ensemble of approximately fifty Cesium standards and ten Hydrogen masers. The Master Clock is a real-time realization of this time scale which is steered to be close to UTC(BIPM), the international standard maintained by the Bureau International des Poids et Mesures. The AMC is a backup to the Washington clock to which it is steered. The Schriever Air Force Base site makes use of two Hydrogen masers and twelve Cesium standards to carry out this responsibility. USNO steers the AMC by means of two-way satellite time transfer (TWSTT) with an accuracy of approximately one nanosecond and common view GPS with an accuracy of approximately five nanoseconds. GPS carrier phase, which may provide sub-nanoseconds time synchronization, is being developed for this purpose also.

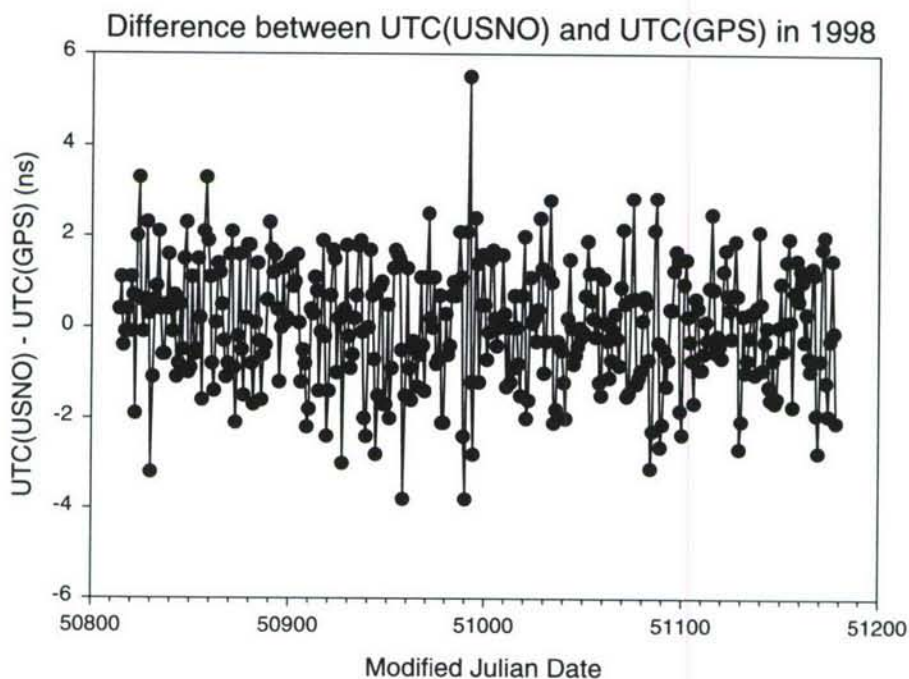


Figure 1. Difference between UTC(USNO) and UTC(GPS) in 1998.

Future Developments

In the future we may expect that advanced communications systems and various space applications will require timing with accuracy better than one nanosecond. Possible future requirements of 0.01 ns accuracy are being discussed today. To meet user demands of the future, the USNO plans to provide one-day predicted GPS orbits accurate to one meter, to develop new time standards, and to develop GPS carrier phase time transfer to its full potential.

GPS orbits accurate to 30 cm and timing of one nanosecond are being envisioned. New time standards being investigated include Cesium fountains and stored ion devices. The USNO Cesium fountain is being developed currently and it is expected to be available for timing experiments in 2001. Further into the future the USNO plans to develop a Distributed Master Clock composed of clocks in space vehicles, as well as standards at stations located around the world. Eventually it is

expected these ultra-precise satellite orbits and clocks will be utilized for navigation in space, an endeavor that will also require new star positions, new algorithms and possibly a new space almanac.

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PRECISE STAR POSITIONS FOR POSITIONING APPLICATIONS

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The Observational Contributions

"The principal aim and object of the Observatory is to assist in perfecting and procuring the requisite data for the American Nautical Almanac."

While that is still part of our mission, today the contributions of the Astrometry Department to the Nautical Almanac are somewhat indirect. Obviously the predictions of star positions are based on good proper motions. We also continue a program of measurements of the planets and their satellites with emphasis lately on the many recently discovered satellites.

However, with our usual foresight and apparently some wishful thinking, the observations alluded to here began in 1846, three years before the legislation that created the almanac. But notice, too, that the writer said "the" Almanac, not "an" almanac. The instruments available at the time seem small by today's standards –

- 14' equatorial of 9" objective
- 7' transit instrument of 5.3" objective
- 5' mural circle of 4" objective
- 30" meridian circle with 5' telescope and 4" aperture
- 6' prime vertical transit instrument with 4.8" objective

These instruments were put into service and the astronomers were instructed that

"A regular series to be kept up on Polaris, Alpha Lyra and 61 Cygni and on the Sun, Moon and planets."

"At least 10 observations with each of the meridianal instruments are to be made on every Nautical Almanac star visible during the year."

In addition (in their spare time) they are "*employed in a systematic review and exploration of the whole heavens, in ascertaining RA, Dec, and assigning a position to every star, cluster and nebula within their reach.*"

The equatorial telescope was used for double star observations and the instruction was to

"Let your observations embrace every double star of which the larger is of the 10th magnitude or under."

This seems like a pretty daunting task, especially in light of the fact that

"There is a regulation of the office, which forbids any of the adjusting screws to be touched without the knowledge of the Superintendent."

Catalogs from Europe, such as Bessel's Zone Observations¹ were available, but it was felt that the United States should be able to produce its own independent catalogs. Orders from the Navy Department explained that "*Because most celebrated European catalogs extend only to 15 degrees south*", then Washington, at 15 degrees further south, should "*commence at the lowest parallel of South Declination which you may find practicable.*"

In a short time the instruments were put into operation and the observations were made so that the first catalog was introduced with the words:

"I have the honor of presenting with this report the first volume of Astronomical Observations that has ever been issued from an institution properly entitled to the name of Observatory on this side of the Atlantic."
Sept 1, 1846 M. F. Maury

All of the previous quotes were taken from the first volume of observations made at the US Naval Observatory.²

Over the next 150 years the Naval Observatory proceeded to produce numerous catalogs of star positions. On February 12, 1898 the Six-inch transit circle made its first observations, eventually producing a series of ten absolute catalogs. Starting in 1879 with the Fundamental Catalog of Auwers, the Astronomischen Rechen Institute produced a series of fundamental catalogs created by combining observations from all

other observed catalogs made throughout the world. The final catalog in the series, FK5, represented the world standard for the optical reference system and the Washington catalogs showed their quality by receiving the lion's share of the weight. When released in 1988 the mean error of stars in the Northern Hemisphere was about 30-40 mas. However, the mean epoch in declination, for example, was 1943 with a mean error of the proper motion of 70-80 mas/century. Thus, today, the mean error of the FK5 has degraded to about 75 mas in the north and considerably worse in the southern sky. In the 1970's plans went forward to measure star positions from an astrometric satellite and in 1989 the European Space Agency launched the Hipparcos mission. The result is the Hipparcos catalog of 100,000 stars with accuracies of a mas or better and the Tycho catalog of one million stars with accuracies of ~ 30 mas. Hipparcos now defines the current optical reference system. However, just as with the FK5, the accuracies of these catalogs began to degrade as soon as the observing was completed. The amount of error is dependent on the error in the proper motion, so some catalogs degrade faster than others (Figure 1).

Improved Proper Motions Are Critical For Improved Positions

At first determining the motions of the stars was quite straightforward (Figure 2) Several observations were made within a very short time period and then they were repeated many years later. With a time span of a quarter of a century the motions could be pretty well established. The error in the proper motion could be reduced by adding more observations at other epochs, by improving the accuracy of the observations or by lengthening the time interval, as in Figure 3. As catalogs were created during the last half of the 19th and throughout the 20th centuries, they were combined to obtain better results, as in the FK series of catalogs. As newer, more accurate, catalogs were added both the mean errors and the systematic errors improved. Continued observing with newer equipment will both lengthen the time span and improve the accuracy. Improvements in the accuracies of older catalogs are still possible by remeasurement and reanalysis of the data and this, too, will improve the global error situation. Recently, we have completed a reanalysis of the great body of data from the Astrographic Catalogue (AC), whose epochs go back to the 1890's. While the accuracy is not great, the long time span makes this an extremely valuable resource for proper motions. The zones making up the AC are not consistent in accuracy and

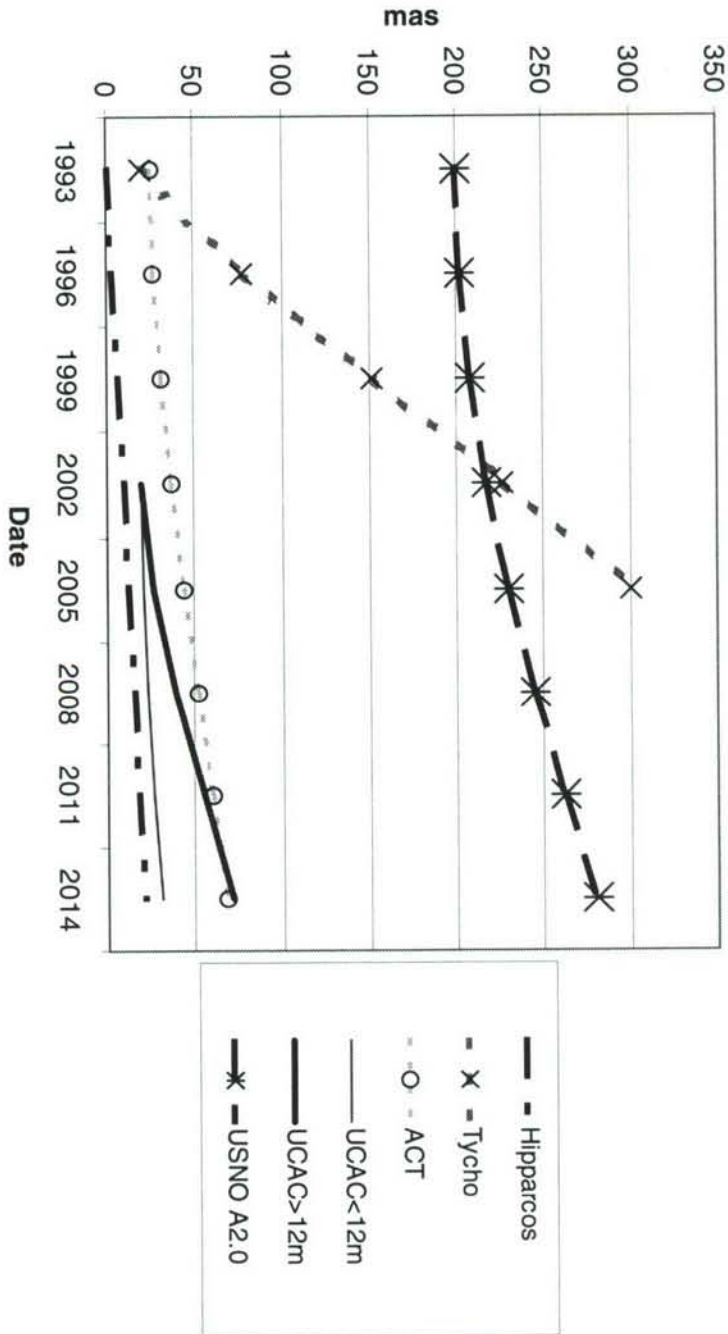


Figure 1 – Positional accuracy degradation with time due to errors in the proper motion

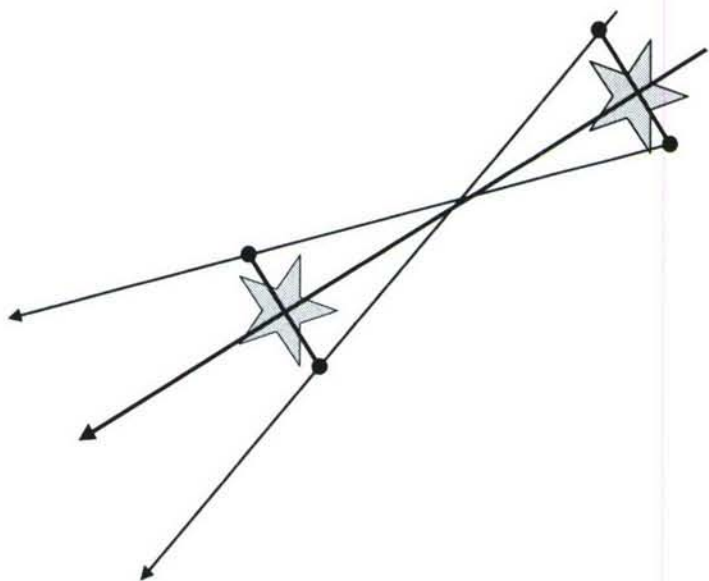
Detected Proper Motion
(1849)

Figure 2 – Proper motion from two positions

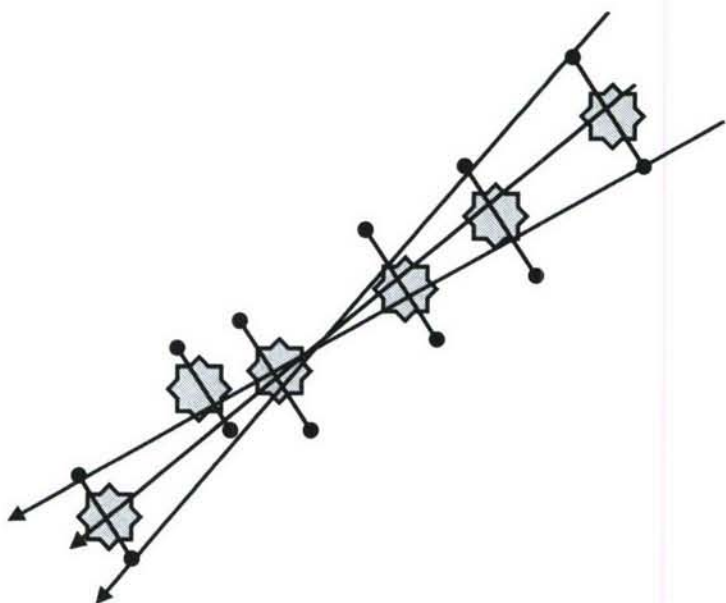
Detected Proper Motion
(1999)

Figure 3 – Proper motion from many positions

it is quite likely that remeasuring the photographic plates from some of the worst zones will yield good dividends in improving the value of this catalog still more. One of the biggest frustrations in astrometry is the lack of uniformity throughout the sky in the older catalogs. For most of history the Southern Hemisphere was vastly under-observed and the individual and systematic errors for the combined (fundamental) catalogs are considerably worse from south of -30° .

However, the biggest improvements come through improvements in the technology. In its $3\frac{1}{2}$ -year mission the Hipparcos satellite measured the positions and parallaxes of over 100,000 stars with accuracies approaching 1 mas. Equally important was its ability to determine the proper motions of the stars to 1 mas/year. Although there are stars as faint as 12th magnitude, the catalog is complete only to magnitude 7.5. The Tycho catalog, obtained by using data from the Hipparcos satellite star mapper, contains 10 times as many stars, but with an accuracy of about 25mas and 25 mas/year proper motion. The availability of the Astrographic Catalogue data made it possible to combine with the Tycho data to create the ACT (Astrographic Catalog/Tycho) Catalog of proper motions with an accuracy of about 3 mas/year. This clearly showed the continued value of combining (good) old observations with modern ones. (Figure 1) The ACT Catalog is available on CD-ROM and has been widely used as the best source of a large number of high accuracy positions and proper motions. In a joint effort between the Tycho Consortium and the US Naval Observatory an additional 1.5 million stars with proper motions will be added to produce the Tycho-II catalog, due in December of this year. These additional data from the star mapper will be of lower quality, but will still represent an important data set.

The Problem Stars

All is not rosy, though. The high accuracies now being obtained introduce problems that never noticeably affected the observations in the past. The most common problem involves the existence of both known and unknown components to the star causing the motion to be non-linear. The FK5 gives orbital data for only seven stars, considered to be fundamental binaries. Many more are unresolved, but have probably affected the observations. If the Hipparcos epoch span is a significant, but not large, fraction of the orbital period of a star, then quite erroneous proper motions can be produced. Here, again, the older catalogs can help to remove the ambiguities by providing a longer baseline. The

Washington Double Star Catalog is the international repository of observational data and can provide orbital parameters for many of these stars.

Figure 4 shows how the color sensitivity of the detector that is used to measure the star's position can introduce additional complications. Figure 5 shows numerous effects caused by a binary star whose components are of different brightnesses and colors and whose orbital period is similar to the length of time of observation. The result is that the true proper motion; that is, the motion of the center of gravity of the system, may be quite different from that measured by any particular instrument at any particular time. Clearly, the determination of the existence of components and their motions is an important issue today. The Naval Observatory Speckle Camera has become an important tool in understanding the Hipparcos problem stars and it is currently being used to investigate the input list for the SIM (Space Interferometry Mission) mission. The 26-inch refractor, installed at the Naval Observatory in 1873, has never been more productive. Observing time has also been obtained on larger telescopes for the Speckle Camera. For stars whose separation is still too close for the Speckle Camera, the Navy Prototype Optical Interferometer (NPOI) will be used to resolve even formerly spectroscopic binaries. The first such, ζ^1 Ursa Majoris, is shown in Figure 6. The NPOI can be used quickly to determine whether a star is binary or not and then with added observations to determine an orbit for the star.

Future Accuracies

From the preceding discussion it is obvious that, although we are achieving unprecedented accuracies, the errors in the proper motions will quickly cause the positions to deteriorate, as shown in Figure 1. Large-scale, ground-based surveys can help. The technology has been improving there also, and the USNO CCD Astrograph Catalog (UCAC) program, now underway at Cerro Tololo, Chile will provide a catalog of over 40 million stars with accuracies similar to the Tycho catalog, but considerably fainter – to at least 16th magnitude. Preliminary data from this project have already been used to provide astrometric reference stars for the Hubble Deep Field South project. We have currently completed the Southern sky from the pole to -35° (Figure 7) and will be issuing a preliminary catalog of positions and proper motions this summer.

Ultimately, more astrometric space missions will be needed. Two missions, SIM and FAME, have major USNO involvement. The SIM

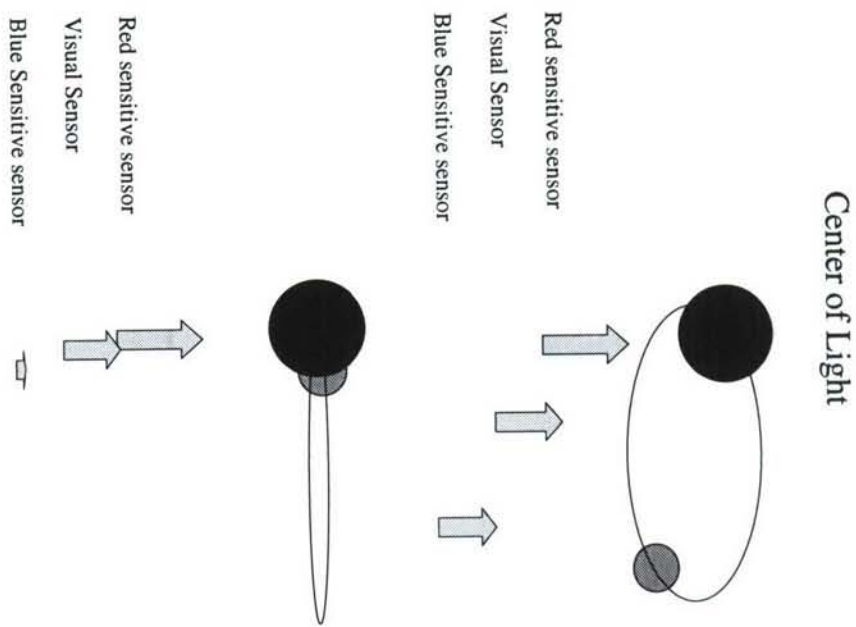


Figure 4 – Center of light varies with color and magnitude

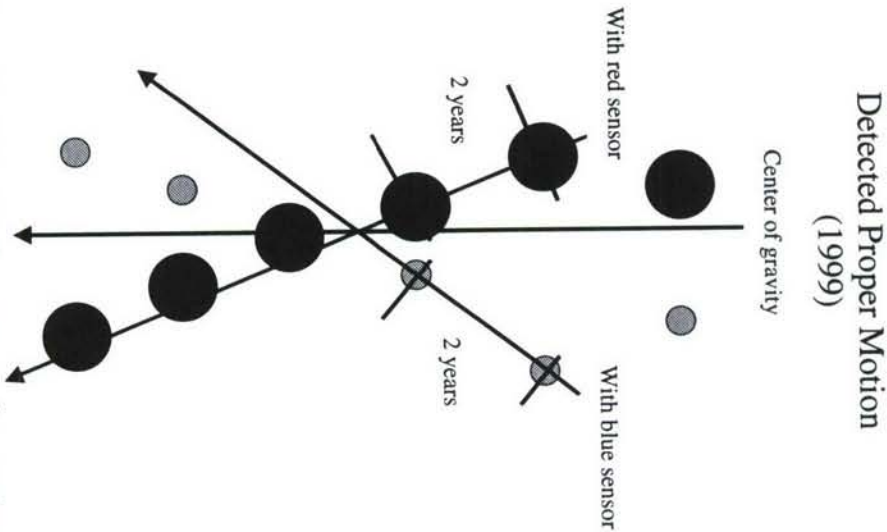
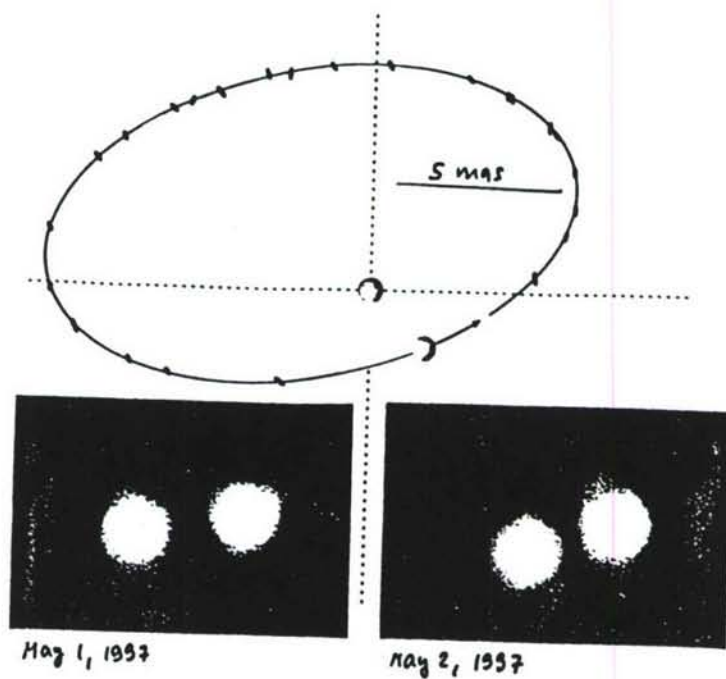


Figure 5 – Calculated proper motion varies with orbital period, color and brightness

Figure 6 - ξ^1 Ursae Majoris as observed with NPOI

UCAC-S FIELDS COMPLETED (20931), 02/21/99

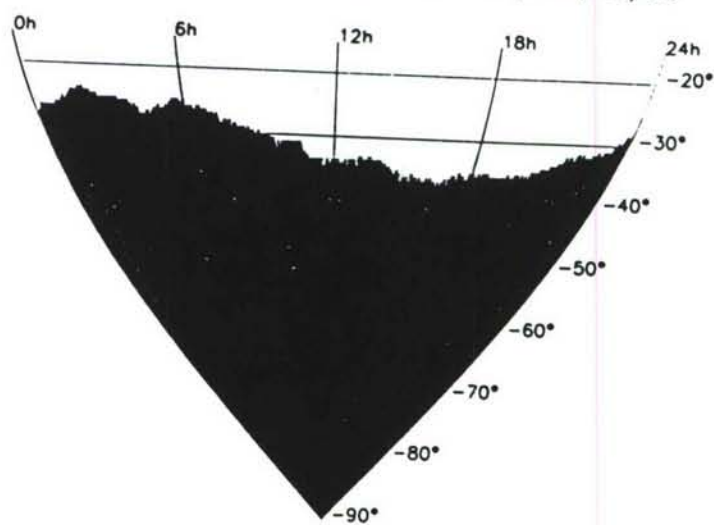


Figure 7

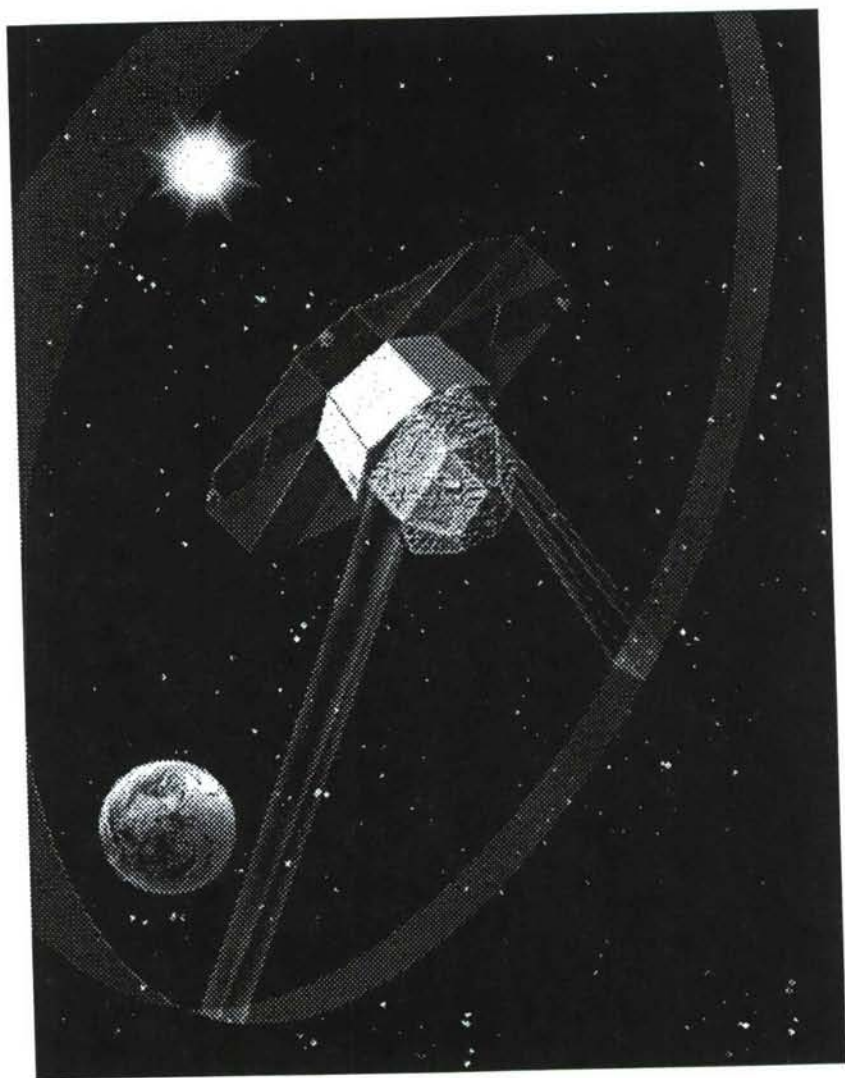


Figure 8 – Proposed Full-Sky Astrometric Mapping Explorer (FAME)
(artists concept)

project is intended to search for extra-solar planets, but in the process will produce about ten thousand star positions with several microarcsecond accuracy. FAME (Full-Sky Astrometric Mapping Explorer), shown in Figure 8, is a totally astrometric mission intended to measure all stars down to 15th magnitude with accuracies of 50-300 microarcseconds. Both of these projects are in the planning stages, but have received initial funding.

Where Do We Stand?

With numerous USNO and other products available to provide star positions for every conceivable purpose, it would seem that we have accomplished Maury's goal. But, of course, we have only begun. Navigation in and into space requires that we provide customized catalogs for use with sensors operating at non-standard wavelengths. The search for faint, fast moving objects is dependent on very accurate catalogs of faint stars. The increasing interest in using infra-red sensors gives impetus to work on an infra-red detector for the NPOI, in addition to the work being done at the Flagstaff Station on infra-red detectors and the USNO collaboration with 2MASS. Certain defense-oriented applications require so-called "clean lists"; that is, lists of stars that meet specific criteria and, to the best of our knowledge, are single points of light. To satisfy this need, we created the Washington Select Star List. From this list we can provide customized data for specific projects, although, as described above, stars that are satisfactory today may not be tomorrow. Finally, the very faintest stars are contained in the massive USNO A2.0 catalog resulting from the measurement with the PMM (Precision Measuring Machine) of the Schmidt telescope surveys. Here are given over five hundred million positions with accuracies of a few tenths of a second of arc.

Generally the accuracies of star catalogs quoted are for the best conditions. All catalogs have upper and lower magnitude limits and the accuracies usually degrade as those limits are approached (Figure 9). It will take a continuing effort (Figure 10) both on the ground, where measures can be repeated over many years, and from space, where greater accuracies can be obtained, to maintain and improve the star positions that form the stellar reference grid.

Further information concerning all projects and catalogs mentioned in this article can be found at the Astrometry Department home page at <http://aries.usno.navy.mil/ad/>.

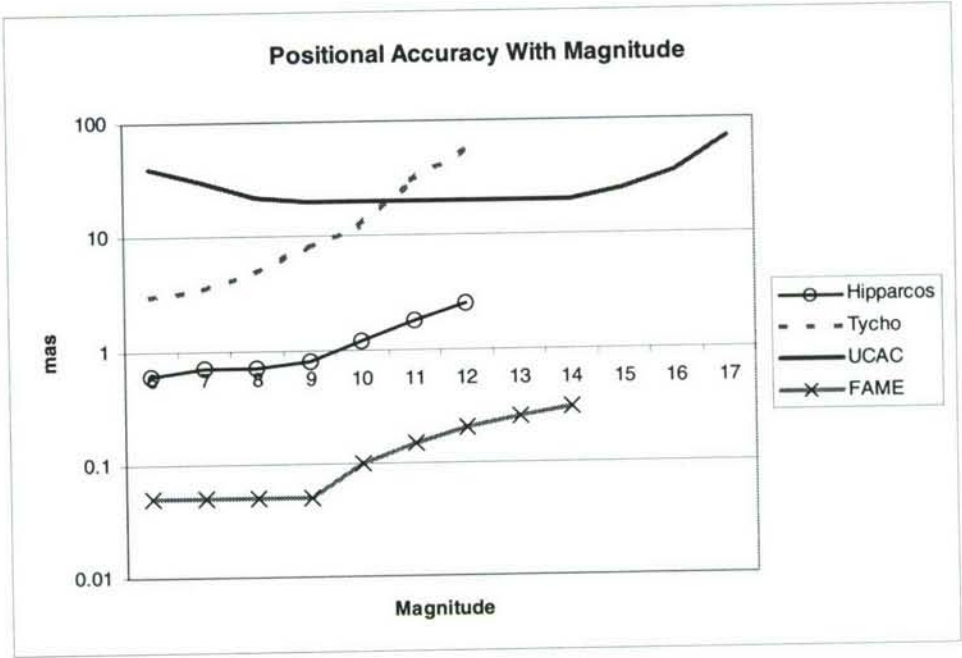


Figure 9 – Accuracy of a catalog varies with magnitude

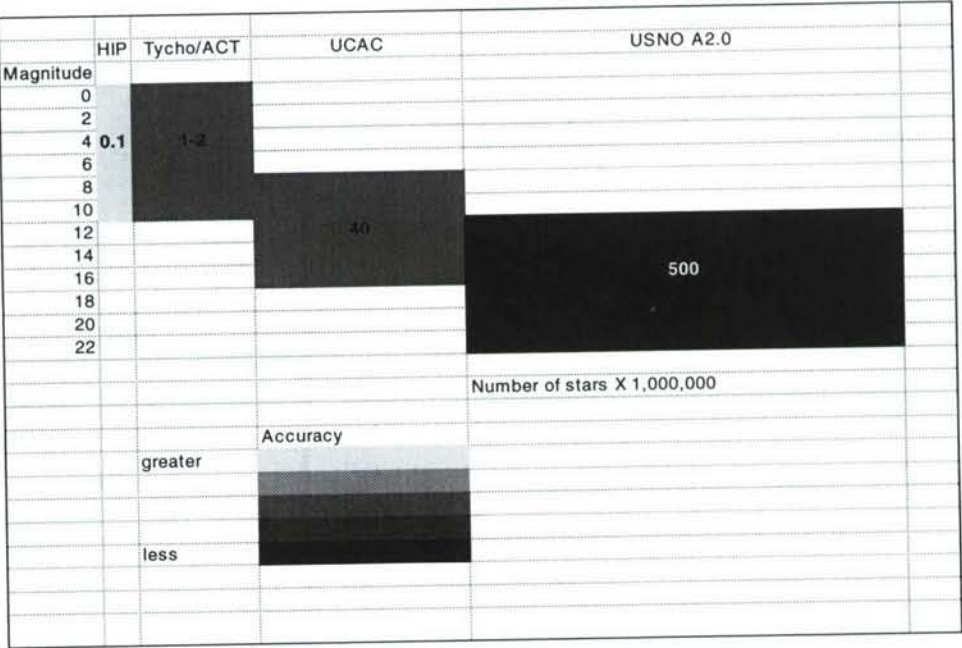


Figure 10 – Current sky coverage

Notes

1. Weisse, Maximilian, Ritter von, "Positiones mediae stellarum fixarum in zonis regionmontanis a Besselio inter $+ 15^{\circ}$ set $+ 45^{\circ}$ s declinationis observatarum, ad annum 1825 eductae et in catalogum ordinatae / auctore Maximiliano Weisse, directore quondam Speculae cracoviensis. Jussu Academiae imperialis petropolitanae edi curavit et praefatus est Otto Struve, Speculae pulcovensis director.", 1798-1863.
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MODERN PLANETARY EPHEMERIDES

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Introduction

The solar system is the premier classical dynamical system in the history of mankind. It certainly has been observed over a longer period of time than any other system; it is one of the most accurately measured; it is a clean system - hardly any friction, hardly any dust, hardly any static; the equations of motion are relatively uncomplicated. In addition, the solar system continues without disturbance from outside: no one can pour it down the sink at the end of the day.

In astronomy, ephemerides are used for everything from astrology to the testing of gravitational theories to the precise navigation of spacecraft. The creation and maintenance of high-accuracy, up-to-date ephemerides involve many different features, including the observational measurements, the detailed physical equations of motion, the perturbations by asteroids, etc.

This paper discusses planetary ephemerides - their uses, their creation, the observational data upon which they are based, their current accuracies, their limitations, and their availability - they come in many different forms.

Uses of Planetary Ephemerides

The uses of planetary ephemerides are presented here, somewhat in order of historical usage.

1) Astrology. At one time, this was probably the main use of ephemerides; even today, there are still those who want to know when Jupiter enters the house of Leo.

2) Maritime navigation. One of the earliest practical uses was navigation, dependent upon the accurate timekeeping determined by astronomers. The ships on the Thames, on the Potomac, etc., would adjust their chronometers according to the latest astronomically measured time of day, visually signaled from the nearby observatories. Our nation's timekeepers are still with the US Naval Observatory.

3) Historical studies. The diverse list includes reductions of older observations, eclipse circumstances, determinations of planetary alignments, calendar calibrations, observer accuracy assessments, etc.

4) Observation predictions and reductions. Especially in modern times, accurate measurements require precise *a priori* positional knowledge; one needs to know exactly where to point the narrow field telescope or antenna or when to expect the return of a radar echo. In fact, it is often the case that the more accurate the prediction is, the more accurately the measurement can be made. Subsequently, after an accurate measurement has been made from the surface of the earth, the signature of the earth's position and velocity must be removed from the measurement.

5) Scientific studies. The testing of alternative theories of gravity, the determination of planetary masses and interiors, etc. - all make use of planetary ephemerides. In fact, the ephemeris improvement program, formerly at MIT, now at the Center for Astrophysics, was originated for the support of such studies.

6) Spacecraft navigation. This is the reason for JPL's ephemeris improvement program. Here, the requirements have been primarily for highly accurate present-day positions.

7) Spacecraft mission planning. "Can the spacecraft actually follow this proposed trajectory?" and "How much fuel will we need to correct the trajectory error due to uncertainties in the ephemeris?" There is often a significant savings in fuel from an accurate ephemeris.

SSDPS : Solar System Data Processing System

From the beginning, the designers of the JPL ephemeris improvement program (SSDPS) made a number of excellent choices. The first two, listed below, are obvious, given the desire for highest possible present-day accuracy; the other two have allowed the program to expand and to be improved with as little complexity as possible.

1) Incorporate all relevant observational measurements into the adjustment procedure. In fact, efforts to obtain new, high-precision data types have been actively pursued - planetary radar, spacecraft tracking, VLBI, etc.

2) Include all known relevant forces into the dynamical model. In this context, the word "relevant" means any effect that can be measured with present technology; as observations become more precise, the modeling of the forces must necessarily be assessed, augmented, and refined.

3) Use numerical methods for the integration of the equations of motion. Once the basic integration program is working and has been validated, any incorporation of modifications to the equations of motion is a

simple, straightforward procedure. Such modifications may arise from improvements to the model as well as from the testing of other theories of gravity. Before the advent of computers, it was necessary to resort to analytical theories. However, the best of these theories has never been able to produce accuracies much better than a milliarcsecond - equivalent to about 1 kilometer at typical distances between the innermost four planets of the solar system. This accuracy is simply inadequate, considering that measurements of these distances are now being taken at the level of a few meters - almost 3 orders of magnitude more accurate. Similarly, the lunar distance is being measured at the level of 2-3 centimeters - a precision completely unattainable with analytical theories.

4) Write the software system in modular form. Each of the many steps of the whole system are self-contained. One is able to add, modify, and/or re-design any part of the system without the danger of affecting the other parts. In addition, partial results are automatically available for checking or analysis. Of course, for the production runs, the pieces are executed in sequence by runscripts, which are themselves easily modified.

Ephemeris Creation

In order to create a new ephemeris, one needs only three things:

1) Equations of Motion. These are simply the mathematically expressed physics as generally accepted. Specifically, general relativity is assumed; a decreasing solar mass is a borderline effect, not yet modeled; the tidal force of the galaxy is negligible. At present, each planetary system (planet plus attendant satellites) is represented in the equations of motion by the system's barycenter. With the exception of the earth and moon, these approximations are presently still below the threshold of significance. The equations of motion are given by Newhall *et al.*¹

2) Integration of the Equations of Motion. This component is a computer program, tested and validated for the required accuracy. The only subsequent changes necessary are modifications or refinements to the equations of motion. There are a few features of the program that are worth noting.

a) There is a very tight requirement for precision: since the moon is measured at the 2-3 cm level, the integration program, in order to support meaningful adjustments, must be an order of magnitude more precise than that; i.e., the integration of the moon's orbit must be no less accurate than just a few millimeters. In the past, the equations were integrated at JPL on a Univac computer, where the double precision word has a 60-bit mantissa.

With the present standard of 53-bit or 54-bit mantissas, double precision is inadequate. Quadruple precision usually brings a 100-fold increase in computing time - unacceptable for long integrations. Fortunately, there is a new compiler now available for PC's which has an extended precision with a 64-bit mantissa. This now seems to be the best choice for integrating the equations of motion.

b) There is a dissipative force in the equations of motion for the moon: friction between the core and the mantle. This acts as a damping effect when integrating forward in time. However, when integrating backward in time, the core-mantle coupling introduces a torque leading to unbounded rotation. This makes it impossible to integrate backward in time for more than a few centuries. For this reason, the friction is suppressed, somewhat artificially, for the backward integration; the friction coefficient is reduced from its normal value to 0 around the latter part of the 19th century. This is accomplished using the factor, $0.5 + \tan^{-1}(\text{JED}-2400000.0)/\pi$, to multiply the friction coefficient.

c) Part of the earth-moon tidal force depends on calculations using the configuration that existed a few hours earlier. This implies interpolation during a forward integration, but it implies a second type of prediction or extrapolation when integrating backward in time. Unlike the core/mantle friction, however, this time-delay feature can be handled by a suitable integration algorithm.

3) Input for the Integration Program. The inputs are the initial conditions and physical constants. The more accurate the input values, the more accurate the resulting ephemeris. The initial conditions and constants, in turn, are a function of a) the observational data to which the ephemerides are adjusted and b) the modeling of the reduction processes. It is the refinement of the input parameters that occupies virtually all of the effort in the improvement of modern planetary ephemerides.

Observational Data

The observational measurements to which the ephemerides are adjusted are the most important part of modern ephemeris improvement.² Table 1 shows the general types of observational data and their accuracies. The unit which is measured (angle or distance) is given in the second column; the equivalent values in the other unit is given in the third column. The striking feature of the table is the increase in accuracy which has come over the past few decades - five orders of magnitude!

Extensive analyses of the data accuracy and of the modeling completeness indicate that the resulting ephemeris accuracy for the inner four planets is about $0''.001$, 1 km, and $0''.02/\text{cty}$ for the relative angles, distances, and inertial mean motions, respectively. There are nearly 30 VLBI observations of spacecraft near planets which have single measurement accuracies of $0''.002$ - $0''.004$ with respect to the International Celestial Reference Frame; they provide the orientation of the inner system, accurate to $0''.001$. The result is that the uncertainties of the four inner planets are about 1-2 km ($0''.001$ - $0''.002$) over the past decade or so, deteriorating to 20 km ($0''.020$) at times which are one century away from the present.

The outer planets rely mostly upon the optical data; the observational accuracy scales roughly with distance (and orbital period); for the more distant planets, older (and less accurate) observations are necessary to complete a full period's worth of measurement. Present angular uncertainties are $0''.03$ - $0''.10$, determined mainly by modern observations. Mean motions, on the other hand, are derived from the full set of observations and are, consequently, susceptible to systematic errors in the older observations. Reasonable estimates for the mean motion uncertainties of the outer planets are about $0''.1/\text{cty}$ for Jupiter and Saturn, $0''.2/\text{cty}$ for Uranus and Neptune, and possibly as much as $0''.5/\text{cty}$ for Pluto.

Table 1. Accuracies of the Observations Fit by the Ephemerides

Inner Four Planets			
optical	0".05-0".5	(35-350 km)	
radar	200 m	(0".0003)	
s/c ranging	7 m	(0".00001)	
LLR	3 cm	(0".00002)	
VLBI/ICRF	0".002	(1-2 km)	
Outer Five Planets			
optical	0".05-0".5	(150-10,000 km)	

Asteroids

There are about 300 asteroids which are massive enough and close enough to Mars and to the earth so that they perturb those bodies significantly; thus, they are modeled in the solar system integrations. Five of them, 1 Ceres, 2 Pallas, 4 Vesta, 7 Iris, and 324 Bamberga, produce distinctive enough signatures to be modeled separately;³ their individual forces are used in the integrations and their masses may be estimated in the adjustments.⁴ The other 295 are classified into 3 taxonomic groups - C, S, and M; they are then assigned a mass, computed from their estimated diameters and from the densities adopted for the three taxonomic groups;⁵ the densities of the three taxonomic groups may be estimated in the ephemeris adjustments.

Despite the modeling attempts, the uncertainties of the asteroid masses remain large, and these are responsible for the largest uncertainties in the ephemerides of the four inner planets. One may perform a "consider covariance" analysis⁶ in order to determine the uncertainties of an ephemeris, resulting from unsolved-for parameters in a least squares adjustment. Such uncertainties cannot be reduced by simply adding more observations; they are not inversely proportional to the square root of the number of observations. Without "considering" the asteroid mass uncertainties, one finds from a *formal* covariance that the earth-Mars range is known and predictable at a level well below 100 m over the present few decades of accurate Mars ranging; this *formal* statistic does indeed scale with $1/\sqrt{n}$; it is completely unrealistic. On the other hand, the consider covariance shows that the *realistic* uncertainty for the earth-Mars range is about 1 km or so. Such a level of uncertainty applies to the whole system of four inner bodies, since the mean motions of the inner system depend to a great extent upon that of Mars.⁷

The realistic uncertainties can be reduced only by improvements to our knowledge of the asteroid masses. Without such improvements, it is necessary to update the observational data base with accurate ranging measurements every couple of years or so, in order to maintain the accuracies at the 1 km level.

Available Ephemerides

Planetary and lunar ephemerides come in all sorts of forms, on many different media, and with a wide range of accuracies. There are interactive websites, programs for PC's, printed tables, lower precision formulae, higher precision ephemerides, and full precision ephemerides. The

following website gives references and provides access to many of these different choices: "<http://ssd.jpl.nasa.gov/iau-comm4>". This is the website for the IAU Commission 4 (Ephemerides); for the ephemerides, themselves, one clicks on "Where to Obtain Ephemerides".

Conclusions

Present-day planetary ephemerides are discussed as two distinct groups, the accurately known inner four planets and the more uncertain outer five planets. The positions of the inner group are known to about $0''.001$ (1 km) with uncertainties in the mean motions of about $0''.02/\text{cty}$. Improvements to the inner planet ephemerides will come only from improvements to the values of the many asteroid masses which affect the motions. Maintenance of the present capabilities requires occasional ranging observations taken every few years.

The ephemerides of the outer planets still rely upon optical observations. Present-day positional accuracies are best provided by recent observations; for predictions away from the present epoch, however, re-reductions of older observations using modern star catalogues would produce worthwhile improvement.

Integrating the equations of motion is no longer the concern that it was before the advent of computers. Especially now with cheap and fast PC's, one may cover many millennia in a matter of hours. There is a feature of the lunar motion, however, which deserves attention: the core-mantle coupling of the moon is a dissipative force - something that can not be integrated backward into the past; the interaction must be artificially suppressed during long backward integrations.

Finally, the long history of printed ephemerides, produced by the national almanac offices, must be noted. Even though there are more modern methods of producing planetary positions with greatly increased accuracies, there is still a need for stability in this field. One can never be completely certain about the sources of numbers used in reductions if they are automated so completely that they come from someone else's "black box". On the other hand, one can be certain about what's printed in the almanac: once it's there, it can't be changed. If someone reports a residual with respect to an almanac, future generations will know what that residual means.

NOTES

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3. J. G. Williams, "Determining Asteroid Masses from Perturbations on Mars", *Icarus*, **57** (1984), 1-13.

4. E. M. Standish and R. W. Hellings, "A Determination of the Masses of Ceres, Pallas and Vesta from their Perturbations upon the Orbit of Mars", *Icarus*, **80** (1989), 326-333.

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6. T. D. Moyer, "Mathematical Formulation of the Double-Precision Orbit Determination Program (DPODP)", *JPL Technical Report*, **32-1527** (1971).

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EPHEMERIDES OF SMALL BODIES OF THE SOLAR SYSTEM

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Introduction

By "small bodies" we usually mean minor planets, comets and satellites, or the objects that come into the purview of IAU Commission 20. For rather obvious reasons, the earth's moon is excluded, and its ephemerides are traditionally handled together with those of the sun and the major planets, objects within the purview of IAU Commission 4. That is the stuff of the various national ephemeris offices, notably of the U.S. Nautical Almanac Office whose 150th anniversary we are currently celebrating, and of H.M. Nautical Almanac Office, with which the U.S. office is closely allied. This is not to say that these offices, as well as their longstanding counterparts in France and Germany, have no interest in the ephemerides of the small bodies, but the historical development of the different types of ephemerides has clearly been different. As happens so often in astronomy, this difference can be quite confusing to the uninitiated, as is evidenced by the recent discussions on a proper mechanism for handling Pluto. As things currently stand, it would appear that Pluto's satellite Charon can be discussed in this paper, but that there should be no mention of Pluto itself—even though Charon has fully one-eighth the mass of Pluto, whereas Pluto has only one-third the mass of even the smallest of Jupiter's Galilean satellites!

The Galilean satellites are, of course, the small bodies for which predicted ephemerides have been published for the longest period of time. Presumably there were attempts at extrapolating the positions of comets, particularly by the ancient Chinese astronomers as the comets were fading from naked-eye visibility, but there are no records of how this was done. In any case, as Halley stated in 1705:

But all those that consider'd Comets, until the time of *Tycho Brahe* (that great Restorer of Astronomy) believ'd them to be below the Moon, and so took but little notice of them, reckoning them no other than Vapours.¹

This is not quite true, for the fifteenth-century Florentine astronomer Paolo Toscanelli recorded the night-to-night positions of several comets on sky charts with such precision that it is difficult to believe he did not consider them to be true celestial bodies, and there were pre-Tychonian attempts to measure cometary parallaxes. The earliest cometary ephemeris is probably the one prepared by Tycho for the great comet of 1577 at daily intervals for the $2\frac{1}{2}$ months he had it under observation, but he did not publish this until 1588.² Almanacs and broadsides often provided cometary prognostications but not their positions, and even Tycho was not immune from publishing cometary horoscopes.³

Jupiter's Galilean Satellites

Crude predictions, based on circular coplanar orbits, for the Galilean satellites were provided by both Galileo and Marius, the latter paying particular attention to eclipses and occultations. These were followed by improved predictions by Hodierna and Cassini, those from the latter in fact appearing around 1700 in early editions of the *Connaissance des Temps*. Although important contributions were made to the subject by Bradley, the most extensive early work on the Galilean satellites was by Wargentin, whose 1746 tables⁴ were the basis of the charts and eclipse predictions in the British *Nautical Almanac* from its inception in 1767 until 1804. Wargentin was a statistician, and although his successive attempts, over some 35 years, to represent the motions of the satellites showed his obvious frustration with the problem, he nonetheless discovered several of the principal mutual perturbations among the satellites by quite empirical means. His was the last empirical work on the satellites, preceding the theoretical work by Bailly, Lagrange and Laplace and the first thorough derivation of a gravitational theory and orbital constants by Delambre. Delambre's tables⁵ were rather quickly superseded by those of Damoiseau,⁶ which were used as the basis of the ephemerides in the *Nautical Almanac* for almost three-quarters of a century, but it seems that the latter were not entirely independent of the former. During the twentieth century the source of the ephemerides has been mainly the work of Sampson⁷ and Lieske.⁸

It is interesting to note that the diagrams with dots showing the relative positions of the satellites at some appropriate hour each night, together with indications of those satellites then eclipsed or occulted, remained essentially unchanged in the *Nautical Almanac* from 1767

through 1959. The tabulation of phenomena other than eclipses began in 1834, but times of conjunctions were not included until 1896. In contrast, for many years after its inception in 1855 the *American Ephemeris* gave the conjunction times but not the daily diagrams, which did not appear there until 1882. Following the merging of the publications in 1960, the dot diagrams were replaced by illustrations showing continuous curves.

The *Connaissance des Temps* has traditionally provided more information about the Galilean satellites than the British and U.S. publications. Notably, it has included actual geocentric coordinates, while the corresponding heliocentric coordinates have been available in manuscript form. Such coordinates have been used, notably in the *Handbook* of the British Astronomical Association, for the computation of the mutual occultations and eclipses of the satellites.⁹ In recent years, the *Connaissance des Temps* has provided all of its information in terms of Chebyshev and other polynomials, and this includes the satellite phenomena.

Comets

Although Halley spectacularly initiated the computation of cometary orbits on the basis of gravitational theory, his computations were made on comets long gone when he published the results,¹ and there was in fact surprisingly little published for several decades more in the way of cometary ephemerides. By the mid-1750s the anticipated return of Halley's celebrated comet resulted in a flurry of activity, although since the detailed and rather accurate prediction by Clairaut and his colleagues was not completed until late 1758, the uncertainty was initially considered to be a couple of years. This meant the production of ephemerides corresponding to perihelion dates throughout the year that could be used perennially.¹⁰

Messier's successful comet-hunting efforts, beginning in the 1760s, brought the regular use of the *Mémoires de l'Académie de Paris* for relatively rapid cometary information, followed in 1800 by von Zach's *Monatliche Correspondenz*, generally considered the first journal devoted to astronomy. Beginning in 1811 there was the short-lived *Zeitschrift für Astronomie* and in 1822 the enormously successful *Astronomische Nachrichten*.

Later in the nineteenth century, particularly with the development of telegraphic communication, more rapid procedures for disseminat-

ing cometary ephemerides were being sought. The most noteworthy of these involved an arrangement with the Associated Trans-Atlantic Cable Companies that allowed the free transmission of ten astronomical messages annually between the Secretary of the Smithsonian Institution in Washington and the Astronomer Royal in London. In 1883 the U.S. side was transferred to the Harvard College Observatory and evolved into the *Harvard Observatory Bulletins* and *Harvard Announcement Cards*. The European side evolved into the telegrams and *Circulars* of the International Astronomical Union's Central Bureau for Astronomical Telegrams, from 1922 located in Copenhagen. At the end of 1964 the IAU Bureau was moved to Cambridge, Massachusetts, and the *Harvard Announcement Cards* were terminated.

Cometary information has also often been made available in publications in individual countries. Prominent among these have been the publications of the British Astronomical Association, which began to contain original material already in the 1920s, when—thanks to the work of Crommelin—the Association's *Handbook* became the leading source of predicted ephemerides for returning comets. As with the prediction for Halley's comet in the 1750s the principal uncertainty would be in the time of perihelion passage. This is obviously the case for a comet observed at a single perihelion passage, but it is also true for the best computations using observations at multiple returns, because of the need to allow for the comet's nongravitational reaction to the vaporization of ice in the nucleus and the consequent expulsion of material. Although this effect has been modeled quite successfully in a semiempirical manner for a number of comets,¹¹ it is never entirely predictable. A set of orbital elements for all of the comets predicted to return in the year n is nowadays routinely published in the *Minor Planet Circulars* for May of the year $n - 3$, and these are reproduced in abbreviated form in the *Astronomical Almanac* for the year n . Ephemerides based on these (or other) elements are then likely to appear in a number of publications, notably in the *Handbook* of the *International Comet Quarterly* closer to the time they are actually needed.

Minor planets

The early orbital and ephemeris information on the first four minor planets was provided mainly in the *Monatliche Correspondenz* and the *Berliner Astronomischer Jahrbuch*. Ephemerides first appeared in the *Nautical Almanac* in 1834. The *Astronomische Nachrichten* and

Berliner Astronomischer Jahrbuch were also the principal publications for data on the minor planets discovered in the 1840s and beyond. The *Nautical Almanac* and *American Ephemeris* made an attempt to accommodate these new discoveries, one particular achievement of the latter being the tabulation, as a supplement to the 1861 edition, of the elements of the first 55 minor planets and of 1859 ephemerides for 33 of them. (This supplement also provided orbital elements for seven of the first eight multiple-apparition comets, 7P/d'Arrest being omitted.) An interesting feature of this supplement is the introduction of what was termed the "Asteroid Epoch", namely, Washington mean noon on Julian Date 2400 000 (1858 Nov. 16). Not only was this intended to be the osculation epoch for the orbital elements, but the elements were to be referred to the mean equinox and ecliptic of that date. Only the latter was actually accomplished; use of the former was deferred until "the next volume", although that never in fact materialized.

In subsequent volumes of the *Nautical Almanac* and the *American Ephemeris* the data on minor planets were restricted to the first four, and even these disappeared after the volumes for 1915. It was around this time that the data on minor planets in the *Berliner Astronomischer Jahrbuch* were transferred to the Astronomisches Rechen-Institut's separate publication *Kleine Planeten*, providing orbital elements and ephemerides for then some 800 objects. After World War II, when the number had increased to 1564, the corresponding publication was produced by the Institute for Theoretical Astronomy in what was then Leningrad under the title *Efemeridy Malykh Planet*, while data on unnumbered minor planets and the collection of observations generally was by the Minor Planet Center, under Herget's direction in Cincinnati until its transfer to Cambridge, Mass., in 1978.¹²

More detailed ephemerides for the first four minor planets, particularly an original high-precision ephemeris for (4) Vesta from Leveau's second-order theory, consistently appeared in the British Astronomical Association's *Handbook* for some two decades after its inception in 1922. Following the publication of an issue of the *Astronomical Papers* of the American Ephemeris with rectangular coordinates,¹³ the 1952 edition of the *American Ephemeris* again contained high-precision ephemerides for the first four bodies. These were initially apparent ephemerides, but they were later replaced by astrometric ephemerides, for equinox 1950.0 from 1960 and for equinox 2000.0 from 1984. Beginning in 1984, the *Astronomical Almanac* has each year included orbital elements for

some 150 bright minor planets at a standard osculation epoch during the year. The selection involves only objects that come to opposition during the year, but no ephemerides are provided.

NEOs and TNOs

What are generally termed "minor planets" (or "asteroids") nowadays extend far beyond the region in the solar system occupied by the first four and the other early discoveries. Already in 1898, (433) Eros was found with a perihelion distance of 1.13 AU and the possibility of quite close approaches to the earth, while 1906 brought the discovery of (588) Achilles, the first of the "Trojans" in the orbit of Jupiter. In more recent times, the range of the numbered objects has been extended to from inside the orbit of Mercury to beyond the orbit of Neptune, the extremes being a perihelion distance of 0.14 AU for (3200) Phaethon and an aphelion distance of 37 AU for (7066) Nessus.

An NEO, or "Near-Earth Object", is quite arbitrarily taken to be an object (asteroid or comet) with a perihelion distance of 1.30 AU or less, ostensibly on the grounds that such an object may eventually be a danger to the earth. This limit is perhaps too small for a comet that could be dramatically perturbed by Jupiter in a matter of 10^2 years, whereas for an asteroid currently even as far out as Eros, an impact is really quite unlikely in 10^5 years. Given that there is a practical interest only in impacts on the earth that could occur within a few times 10^2 years by objects large enough to do widespread damage, it tends therefore to be more useful to speak of a PHA, or "Potentially Hazardous Asteroid", which is defined to have an absolute magnitude of 22.0 or brighter (i.e., a probable diameter of more than 200 meters) and a current orbit that brings the object within 0.05 AU of the earth, the orbit of the latter being considered for this purpose to be a circle of radius 1 AU.

Some idea of the rate of progress in discovering the PHAs comes from considering that the first one was discovered only in 1932 (and was promptly lost until its recovery in 1973), and that just 17 PHAs had been recognized by 1980. Thanks in particular to the photographic patrol by Helin with the 0.46-m Schmidt at Palomar and the scanning-CCD "Spacewatch" program of Gehrels at the University of Arizona, together with the examination by McNaught of U.K. Schmidt plates, the number of PHAs had increased to 104 by the end of 1997, the largest number of finds in one year being the 13 in 1994, the last year

of the search programs at Palomar. In 1998 the number of new PHAs discovered was a whopping 55, as many as 35 of these being due to LINEAR, an extensive CCD patrol conducted by MIT's Lincoln Laboratory, using satellite-tracking equipment in New Mexico.

NASA has recently committed itself to the aim of discovering 90-percent of the kilometer-sized NEOs in ten years. While success in only ten years is completely unrealistic, given the need for follow-up observations, the existence of LINEAR has provided a tremendous boost, and maintenance of activity at the level of that of the past twelve months suggests that the stated discovery aim could be completed by 2030. The need for follow-up observations should not be taken lightly, because only 66 of the currently known 165 PHAs have been observed at more than one opposition. Until a few years ago, orbital elements and ephemerides for at least the more interesting of the newly discovered asteroidal NEOs were included, like those of the comets, in the IAU *Circulars*. Data on the asteroidal NEOs (as well as some of the cometary follow-up material) have since Sept. 1993 been provided in a series of *Minor Planet Electronic Circulars* that can be quickly produced in a semiautomatic manner.

Although the TNOs, "Transneptunian Objects", are at the opposite extreme of the solar system, much of what applies to their "maintenance" is similar to that involving the NEOs. The first TNO was Pluto, an ephemeris for which was included already in the British Astronomical Association's *Handbook* for 1931, together with this note:

On 1930 March 13, the 149th anniversary of the discovery of Uranus, the Lowell Observatory announced the successful termination of a long search for a trans-Neptunian body corresponding approximately with the prediction of the late Prof. Lowell... A preliminary orbit showed great eccentricity, and it has even been suggested that the body is a comet, and a hyperbolic orbit has been suggested. But examination of plates taken in 1919, 1921 and 1927 show [sic] objects the positions of which are consistent with identity with the new object, and from these, elements have been derived by E. C. Bower and F. L. Whipple.¹⁴

No ephemeris for Pluto in fact appeared in the *Nautical Almanac* or the *American Ephemeris* until 1950, with 1931-vintage elements by Bower being used for the purpose. What settled the appearance of Pluto

in these publications, however, was the determination of its mass as $1/360\,000$ that of the sun and its inclusion with the four giant planets in the monumental mid-century numerical integration of these bodies over the years 1653–2060 on the Selective Sequence Electronic Computer.¹⁵ As indicated earlier, this mass determination, comparable to that of the earth, is quite erroneous, and it was being questioned by one of the authors of the numerical integration only a few years later.¹⁶

Although the suggestion that Pluto was just the largest member of a belt of 22nd magnitude (100-km) “cometesimals” at 40–50 AU from the sun was made by Whipple as long ago as 1964,¹⁷ the new technology necessary to detect these fainter bodies did not permit success until the discovery of 1992 QB₁ by Jewitt and Luu. Five more TNOs were added by the end of 1993, 30 more by mid-1996, and another 29 by early 1998. Of these first 66 objects, 45 have so far been observed at a second opposition. The past year alone has seen this number double, and follow-up of these objects, generally in the magnitude 23–24 range, has clearly become a problem, despite the usual prompt publication of initial ephemerides in the *Minor Planet Electronic Circulars*. In the case of a TNO, even the second-opposition observations are sometimes insufficient to provide more than a guess at the orbit, and at least one of the two-opposition TNOs is now lost.

Nevertheless, examination of the multiple-opposition TNO orbits has made it possible to amass some information about the distribution of the TNO orbits. It appears that there is a “main belt” of TNOs, sometimes called *cubewanos* from their prototype 1992 QB₁, with orbits having semimajor axes a in the range 41–47 AU. Although orbits in the inner part of this belt are of low eccentricity, and even those in the outer part rarely have eccentricities e as high as 0.2, there is a significant distribution in inclination i , certainly to 30°, and perhaps higher. The objects seem to have orbits that are quite stable against perturbations by Neptune, the minimum approach distance to that planet being perhaps 9 AU.

Next in order of decreasing population is a group of TNOs with a around 39–40 AU, e in the range 0.1–0.3 and i up to perhaps 20°. The significance of these objects is that, although those with the more eccentric orbits cross the orbit of Neptune, all are in 2:3 resonance with that planet and are thereby prevented from making close approaches to it. The actual minimum approach distance to Neptune is perhaps 11 AU, although the objects with the more eccentric orbits can approach

within 8 AU of Uranus. Pluto itself is a member of this population, the members being widely known as *plutinos*. Allowing for the fact that the observed cubewanos are generally farther away than the observed plutinos, there are perhaps three times as many of the former as the latter. One TNO is known to exist at the 3:4 Neptune resonance ($a \sim 36$ AU), one at the 3:5 resonance ($a \sim 42$ AU, $e \sim 0.2$) and two, it seems, at the 1:2 resonance ($a \sim 48$ AU, $e \sim 0.4$). Whether low- e TNOs exist beyond the 1:2 resonance is currently unclear, but 1996 TL₆₆ has an orbit with $e \sim 0.6$ and its perihelion at 35 AU.

A convenient way to look at the relationship between the elements of a heliocentric orbit and the projected position on the sky in which an observer on the surface of the earth will see the object involves combination of the equations

$$\rho_i \hat{\rho}_i = \mathbf{r}_i + \mathbf{R}_i, \quad (1)$$

and

$$\mathbf{r}_i = f_i \mathbf{r}_0 + g_i \dot{\mathbf{r}}_0, \quad (2)$$

where the subscripts pertain to quantities at discrete times t_i (where $i = 0, 1, 2, \dots$), \mathbf{r}_i being the object's heliocentric position vector, $\dot{\mathbf{r}}_i$ its heliocentric velocity vector, \mathbf{R}_i the vector from the observer to the sun and $\hat{\rho}_i$ the unit vector from the observer to the object. In addition, ρ_i is the scalar distance from the observer to the object, and the factors f_i and g_i have validity only when the perturbations by other planetary bodies are ignored, in which case the values of the six keplerian elements that can be derived from \mathbf{r}_0 and $\dot{\mathbf{r}}_0$ are independent of the time specifically selected for t_0 . There are also well-known expressions giving f_i and g_i involving these elements and knowledge of the time difference $t_i - t_0$.

With allowance for minor effects (such as the finite speed of light), Eqs. (1) and (2) contain the essence of the orbit problem, whether one is computing sky positions from orbital elements or *vice versa*. In the latter case, rigorous values of f_i and g_i cannot be computed until some approximation to the orbital elements is available. Initially, it is generally sufficient to approximate them by

$$f_i = 1 - \frac{1}{2} \frac{\tau_i^2}{r_0^3}, \quad g_i = \tau_i \left(1 - \frac{1}{6} \frac{\tau_i^2}{r_0^3} \right), \quad (3)$$

where $\tau_i = k(t_i - t_0)$, with $k = 0.01720209895$ when the time is in days, $r_0 = |\mathbf{r}_0|$ and the distance is in astronomical units, and the mass of

the object with respect to the sun is neglected. Further terms in these expansions depend also on $r_0\dot{r}_0 = \dot{\mathbf{r}}_0 \cdot \mathbf{r}_0$ and $v_0 = |\dot{\mathbf{r}}_0|$, but they can be ignored as long as τ_1 is sufficiently small. Obviously, $f_0 = 1$, $g_0 = 0$. With observations of $\hat{\rho}_1$ and knowledge of \mathbf{R}_i at times t_0 , t_1 and t_2 , the nine scalar equations corresponding to the combination of Eqs. (1) and (2) and the use of Eqs. (3) allow, at least in principle, the computation of the six keplerian elements and the distances ρ_0 , ρ_1 and ρ_2 .

In practice, as already implied, the errors associated with a general orbit solution for a TNO at a single opposition are so enormous that such a solution is almost always useless for pinpointing sky positions at a future opposition—given that the objects are so faint that large, narrow-field instruments are needed for the observations. It is usually therefore preferable to take just two observations (at least for an initial solution) and make two additional assumptions about the orbit that are not obviously incompatible with what one expects of TNOs. Of course, in doing this, there is the danger that an object that happens to have a hitherto unrecognized type of orbit will be lost, but given that observing time on large telescopes is at a premium, this is a risk that has to be taken, if there is to be any hope of collecting useful data on TNOs in any quantity.

It is well known that orbit computations can be considerably simplified by making a rotation of the coordinate system so that the reference plane passes through two of the observations, with one of the axes directed at one of them.¹⁸ Given only the two observations at times t_0 and t_1 , this can be conveniently accomplished by post-multiplying the row vectors $\hat{\rho}_i$ and \mathbf{R}_i (for $i = 0, 1$) by the orthogonal matrix whose columns are the components of

$$\hat{\mathbf{i}} = \hat{\rho}_1, \quad \hat{\mathbf{j}} = \hat{\mathbf{k}} \times \hat{\mathbf{i}}, \quad \hat{\mathbf{k}} = \frac{\hat{\rho}_1 \times \hat{\rho}_0}{|\hat{\rho}_1 \times \hat{\rho}_0|}. \quad (4)$$

If the rotated components of $\hat{\rho}_i$ are denoted by $(l_0, m_0, n_0 = 0)$ and $(l_1 = 1, m_1 = 0, n_1 = 0)$ and those of \mathbf{R}_i by (X_0, Y_0, Z_0) and (X_1, Y_1, Z_1) , with those of \mathbf{r}_0 and $\dot{\mathbf{r}}_0$ being (x_0, y_0, z_0) and $(\dot{x}_0, \dot{y}_0, \dot{z}_0)$, respectively, the combination of Eqs. (1) and (2) simplifies to

$$x_0 = \rho_0 l_0 - X_0, \quad y_0 = \rho_0 m_0 - Y_0, \quad z_0 = -Z_0, \quad (5)$$

and

$$f_1 x_0 + g_1 \dot{x}_0 + X_1 = \rho_1, \quad f_1 y_0 + g_1 \dot{y}_0 + Y_1 = 0, \quad f_1 z_0 + g_1 \dot{z}_0 + Z_1 = 0. \quad (6)$$

To obtain orbit solutions that fit the two observations it is now simply a matter of taking trial values of ρ_0 , computing the components of \mathbf{r}_0 from Eqs. (5), f_1 and g_1 from Eqs. (3), then \dot{y}_0 and \dot{z}_0 from the second and third of Eqs. (6). There remains the first of Eqs. (6), containing the two unknowns \dot{x}_0 and ρ_1 , and this is best handled by taking trial values also of \dot{x}_0 .

In doing this, it is useful to see from the energy integral, which relates r_0 , v_0 and the semimajor axis a , that

$$\dot{x}_0^2 = k^2 \left(\frac{2}{r_0} - \frac{1}{a} \right) - \dot{y}_0^2 - \dot{z}_0^2. \quad (7)$$

A particular choice of a , such as might be selected to examine whether a TNO is a plutino (or, perhaps, in some other resonance with Neptune), therefore yields a positive and the corresponding negative value of \dot{x}_0 , each of which can be used in the first of Eqs. (6) to calculate ρ_1 , as well as with the other components of \mathbf{r}_0 and $\dot{\mathbf{r}}_0$ to yield a complete set of orbital elements (after rotation back into the original reference system). It is also useful to consider the case when $\dot{x}_0 = 0$, because this yields the smallest possible a for the selected value of ρ_0 .

Another significant value of \dot{x}_0 is that given by

$$\dot{x}_0 = - \left(\frac{y_0 \dot{y}_0 + z_0 \dot{z}_0}{x_0} \right). \quad (8)$$

This value, yielding $r_0 \dot{r}_0 = 0$, places the object at perihelion or aphelion. In practice, at least for a TNO near opposition, this apsidal solution is not greatly different from the $\dot{x}_0 = 0$ case. Apsidal orbits are an important tool first discussed by Väisälä,¹⁹ but without the rotation specified by Eqs. (4). Use of this rotation makes the discussion much more general.

If there is value in computing apsidal orbits, where the true anomaly is 0 or 180°, it might also be reasonable to consider *lateral orbits*, in which the true anomaly is $\pm 90^\circ$ and the object on the *latus rectum*. Such a solution requires that $r_0 = p$, where

$$k^2 p = r_0^2 v_0^2 - (r_0 \dot{r}_0)^2, \quad (9)$$

thereby establishing \dot{x}_0 by means of the quadratic equation

$$\dot{x}_0^2 (y_0^2 + z_0^2) - 2 \dot{x}_0 x_0 (\dot{y}_0 y_0 + \dot{z}_0 z_0) + [r_0^2 (\dot{y}_0^2 + \dot{z}_0^2) - (\dot{y}_0 y_0 + \dot{z}_0 z_0)^2 - k^2 r_0] = 0. \quad (10)$$

The numerically larger root will invariably yield a hyperbolic solution, and even the numerically smaller root will yield an ellipse for a very limited range of ρ_0 . Lateral orbits can be particularly useful for NEOs, where a perihelic solution near opposition may just not be realistic. If there is in fact a circular orbit for the selected value of ρ_0 , the \dot{x}_0 values corresponding to this lateral solution and to the apsidal solution will be identical.

For new candidate TNOs, however, the best approach to adopting orbital elements with a chance of producing a reasonably meaningful ephemeris seems to be to use two observations to compute a series of apsidal orbits for values of $\rho_0 < 1$ AU to, say, 50 AU. Small ρ_0 means that the object is not a TNO, of course, but if the object is far enough from opposition that there may be confusion with a main-belt minor planet near its stationary point (or, indeed, if the object is an NEO headed more-or-less directly toward the earth), it is important to try to eliminate such a possibility by examining whether observations made over the course of several hours (if, indeed, the available observations are on separate nights) show the effect of parallax. A near-earth orbit solution for a genuine TNO near opposition will also tend to give an extremely small orbital inclination. Even a small increase in ρ_0 then quickly increases e , even to hyperbolic values. As ρ_0 increases to 20 AU and more, e and a decrease again, and the distance corresponding to a circular orbit can be interpolated. Beyond that the orbits shift from perihelic to aphelic, with a continuing to decrease but e again increasing, together with i , which will quickly reach retrograde values. These solutions do not seem to have physical relevance, but it is useful to know that they exist, particularly as a then increases again and e decreases to a retrograde circular solution.

In practice, if the direct circular orbit has a in the acceptable range, it is probably reasonable to adopt it for the solution. If this circle gives $a \sim 47$ –48 AU, it may be desirable to increase ρ_0 a little in order to place the object at the aphelion of a slightly smaller orbit. Likewise, if the circular $a \sim 40$ –41 AU, a small decrease in ρ_0 will place the object at the perihelion of a slightly larger orbit. If the circular solution has $a \sim 36$ AU and smaller, perhaps even below 30 AU, it becomes appropriate to look into the possibility of a resonance with Neptune. In doing so, it is necessary to be aware of the object's angular elongation ϵ from Neptune. If $\epsilon \sim 90^\circ$, it is quite likely that the object will be a plutino near perihelion. If there is some departure of ϵ from 90° , and

particularly if the circular a is in fact slightly larger than 36 AU, more skillful manipulation of the orbital procedure outlined above may be appropriate, perhaps to give a plutino that is somewhat removed from perihelion and therefore of larger e and more likely to stay away from Neptune.

By the same token, some of the objects with circular a in cubewano range and that are in conjunction with or in opposition to Neptune will in fact be plutinos in the aphelic portions of their orbits, but it is not possible to distinguish such cases from a short observed arc. An object with small circular a that is opposite Neptune is likely to be stabilized by some other resonance with Neptune, such as 3:4 or 3:5. In any case, one always has to be aware that an object observed at these distances may be in a much more eccentric orbit, as in the "scattered-disk" case 1996 TL₆₆ near perihelion, or for a "centaur" (with semimajor axis and perihelion in the range of the giant planets) that might be observed near aphelion. It is therefore important to appreciate that the preliminary orbit calculations for TNO candidates are always simply the outcome of informed guesses and will prove to be noticeably in error in a significant fraction of the cases. An appropriate regimen of follow-up observations, certainly extending over 60 days at the first opposition, is therefore essential if more is to be learned about the true nature of the transneptunian belt.

Other inner satellites

The 1882 edition of the *American Ephemeris* contained for the first time diagrams and ephemerides for greatest elongations, in most instances due to Newcomb, for the first eight satellites of Saturn, the first four satellites of Uranus, the first satellite of Neptune and (from 1886 for the elongations) the two satellites of Mars (discovered only in 1877). The *Nautical Almanac* began carrying information about these satellites in 1899. Beginning in 1912 (in 1920 for the satellites of Mars), quantities were provided for computing the apparent distances and position angles at other times. Times of conjunction were given for Saturn VIII (Iapetus) already in 1882, and they were added for Saturn VI (Titan) and VII (Hyperion) in 1938. For most of the twentieth century, the ephemerides for almost all of the satellites of Mars, Saturn and Uranus have been derived from the work of H. and G. Struve.

Data for the fifth satellite of Jupiter (discovered in 1892) were introduced in the *American Ephemeris* in 1898 (and in the *Nautical Almanac*

in 1906). Data for the fifth satellite of Uranus and the satellite of Pluto (discovered in 1948 and 1978, respectively) were added in 1981 (when the combined publication was renamed the *Astronomical Almanac*), although the latter satellite had not then been completely resolved from the primary, and the quantities for computing apparent distance and position angle were not provided until 1990.

Eclipses, occultations and transits involving Saturn's satellites occur for a few years around the times of ring-plane passage, and predictions for the four brightest satellites have traditionally been provided in the *Handbook* of the British Astronomical Association. Indeed, it was the need for such computations that provided an important impetus for establishing this publication.²⁰

No printed ephemerides are provided for the inner satellites found, mainly from the Voyager 2 mission, during 1979–1989. These satellites include three more interior to Jupiter I (Io), the six interior to Saturn I (Mimas), two additional faint bodies in the orbit of Saturn III (Tethys), one in the orbit of Saturn IV (Dione), the ten interior to Uranus V (Miranda) and the six interior to Neptune I (Triton). Two of these new Saturnian satellites, also sharing the same orbit, were suspected from ground-based observations at the ring-plane passage in 1966, but this resonant situation was not appreciated until further observations were made at the next such passage in 1980. Several additional probable Saturnian satellites were detected in 1980, from Voyager and from the ground, and again in 1995, this time from Hubble Space Telescope and the ground, although there does not appear to be enough information to make further linkages.

Although the *Connaissance des Temps* has long provided very detailed material on the Jupiter's Galilean satellites, it has begun to attend to other satellites only recently. A 1980 supplement contained polynomial coefficients for the traditional satellites of Mars, Saturn and Uranus, and polynomials for computing tangential differential coordinates are now routinely included in the main publication. There is still no ephemeris for Triton. This satellite work is still under development, and according to Arlot, the next object for which ephemerides will be provided is Jupiter XIV (Thebe).

Outer Satellites

The first outer (irregular) satellites to be discovered, during 1898–1905, were Saturn IX (Phoebe), Jupiter VI (Himalia) and Jupiter VII

(Elara). Predictions for the differences in right ascension and declination with respect to the primary have been consistently tabulated in the *American Ephemeris* from 1912 onward (and sporadically from 1909), initially using the orbital computations by Ross. (Differential coordinates for Hyperion and Iapetus have also been provided since 1960, following the amalgamation with the *Nautical Almanac*, which was already publishing these in the 1930s.)

Although Jupiter VIII was discovered in 1908, and Jupiter IX-XII followed between 1914 and 1951, the systematic publication of ephemerides of these irregular satellites did not occur until 1968, when Herget published a numerical integration of the orbits and differential and absolute ephemerides through the end of the century.²¹ Differential ephemerides, also for Jupiter XIII (Leda) and Neptune II (Nereid), have been appearing in the *Astronomical Almanac* since 1981. Polynomial coefficients for both differential and absolute ephemerides for the outer satellites of Jupiter and Saturn have also been published in recent years in the supplement to the *Connaissance des Temps*. There is considerable merit to having absolute ephemerides for all of the outer satellites. This allows more direct comparison with the observations, which are also nowadays almost exclusively in the form of absolute positions. This of course is also the form in which observations of minor planets are reported. Indeed, observations of outer satellites are sometimes accidentally reported as being of minor planets.

The discovery of Uranus XVI (Caliban) and XVII (Sycorax) in 1997 now means that all four of the giant planets possess outer satellites, probably captured from the centaurs, and they bring to 12 the total complement of such satellites.²²

Electronic ephemerides

Do observers really need printed ephemerides nowadays, as long as orbital elements are provided, and given the widespread availability of appropriate computer software? This is a good question, and it is one that has been asked from time to time at meetings of IAU Commission 20 during the past two decades. Particularly in the case of minor planets, the number of observable objects has been increasing exponentially, and the amount of space devoted to printed ephemerides has tended to grow in like manner.

In olden times, ephemerides for the numbered minor planets were published to 1-armin precision for six (earlier, seven) dates at 10-day

(earlier, 8-day) intervals around opposition. First differences were provided to aid interpolation, and observers were often quite adept at allowing for second differences mentally. Much the same was true for comets and particularly unusual minor planets, except that the ephemerides extended further from opposition, and shorter time intervals might be used in order to guarantee that second-difference interpolation was sufficient. Already in the 1960s, there was some pressure to have ephemerides printed to 0.1 arcmin, not because they were more accurate than earlier, but to allow a better definition of the apparent motion for the purpose of offsetting it during an exposure tracked on the moving object, rather than on the field stars. There was also pressure to have routine ephemerides further from opposition, notably for the new discoveries and identifications in the *Minor Planet Circulars*, but also in *Efemeridy Malykh Planet*. As a result, the latter had to decrease the number of opposition ephemerides per printed page from 14 to 12. The publication of the differences went by the wayside when the ephemeris precision was increased in *Efemeridy Malykh Planet* in 1989. Judicious use of differences can save space, however, and during 1991–1993 the *Minor Planet Circulars* made use of a format that provided just two ephemeris positions generally 30 days apart with first and second differences permitting extrapolation to a 50-day span.

As a preliminary to having observers compute their own ephemerides, the recommendation was made at a meeting of IAU Commission 20 in 1976 to use a single osculation epoch for the orbital elements of all the minor planets. Harking back to the never-implemented suggestion in the supplement to the 1861 *American Ephemeris*, this epoch was to be latest date each year when the Julian Date *modulo* 200 was 0.5. This change was introduced in the 1980 edition of *Efemeridy Malykh Planet*, with the elements also published to greater precision than before. Observers needed a computer program that would, at a minimum, derive unperturbed ephemerides from orbital elements, and they were in business. At this point, the main problem was the availability of the vector \mathbf{R}_i to be used in Eq. (1). To this end, the evaluation of Newcomb's theory of the sun at 4-day intervals throughout the nineteenth and twentieth centuries was already available in the mid-1950s,²³ but to store this in its entirety in early personal computers was a problem. The alternative of computing the vector directly from the theory had merit (also from the point of view that interpolation would not be needed), but this was quite a slow process. A breakthrough for the

IBM PC, for example, occurred with the availability of the mathematical coprocessor in 1983, as this permitted the computation of \mathbf{R}_i for a specified t_i to seven-figure accuracy in less than half a second.

Nevertheless, for many observers, there was some obvious convenience to extracting ephemerides from computer sites set up for the purpose, and this has become commonplace with the rise of the World Wide Web. The first on-line service that included ephemeris computation was put in place by the Minor Planet Center and Central Bureau for Astronomical Telegrams already at the beginning of 1984. This "Computer Service" was established principally to respond to the fiasco in May 1983 when a comet made the closest approach of any comet in more than two centuries. This comet had been announced just a week earlier, and only those who subscribed to the Bureau's telegram service, rather than to the printed *Circulars*, were able to receive updated cometary ephemerides prior to the actual approach. Of course, the Computer Service also included the *Circulars* themselves, and by 1988 these were being routinely sent by e-mail. The Bureau last distributed information in an actual telegram in 1993.

Ephemeris programs have also been provided in diskette form since the mid-1980s. One of the first such programs, using an evaluation of the Newcomb theory for \mathbf{R}_i , was issued by the Minor Planet Center in 1986 with the first diskette edition of the *Catalogue of Cometary Orbits*. Of course, more recent computer programs provided on portable media allow greater sophistication, and there are more than a dozen such programs currently available. Beginning in 1991, *Efemeridy Malykh Planet* became available on diskette in the electronic form *STAMP*.

While the most obvious use of ephemeris generation is to provide predicted positions of a specified object, a secondary use is to allow an observer to identify a particular object. This requires the calculation of ephemerides for a large number of objects (e.g., the numbered minor planets, the numbered short-period comets and currently observable long-period comets) for a single time (or pairs of times) and the presentation of those in a particular region of the sky. Such a feature was added to the Computer Service already in 1986. Of course, it is much the same philosophy that led—long ago—to the ordering of ephemerides by opposition date in *Efemeridy Malykh Planet* and its predecessors. Most of the "ephemerides" in the *Minor Planet Circulars* now consist solely of entries giving position, motion and magnitude at the instant of opposition, together with reference to the latest orbital elements.

As noted, the World Wide Web has, during just the past few years, revolutionized the whole process of ephemeris availability. The more fundamental Web ephemeris sources are immediately updated with the availability of new orbital elements and include such features as topocentric ephemerides for a user-specified location on the earth's surface. The Minor Planet Center, for example, has a free service for ephemerides specifically of comets, TNOs, NEOs, centaurs and selected minor planets (<http://cfa-www.harvard.edu/iau/Ephemerides/>), for the calculation of ephemerides for up to 30 user-specified minor planets (<http://cfa-www.harvard.edu/iau/MPEph/MPEph.html>)—with an optional summary showing the date of the latest known observations or the construction of an 'html' file the user can post on his/her own webpage with ephemerides of objects he/she would like others to observe—as well as a feature (<http://cfa-www.harvard.edu/iau/MPEph/NewObjEphems.html>) allowing the user to generate an ephemeris from, in particular, a pair of observations. As a service to users of many of the commercial ephemeris programs, orbital elements can be extracted in the specific formats utilized by these programs.

Ephemerides for the more established satellites of Mars through Uranus (but not Neptune) are also available from the Natural Satellites Data Center, maintained by IAU Commission 20 at the Bureau des Longitudes (http://www.bdl.fr/ephem/ephemsat_eng.html). The Jet Propulsion Laboratory maintains a more general "Ephemeris Generator" (<http://ssd.jpl.nasa.gov/cgi-bin/eph>) that is particularly useful in that it includes data for all of the known satellites of the four giant planets.

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THE MOON AND THE ALMANACS

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The Problem with the Moon

Of our celestial neighbors the Sun and the Moon are the most apparent and the most readily observed in their orbits. One would expect therefore, that the modeling of the motion of the Moon would be rather straightforward. This has not proven to be the case and the almanac makers' lot with regard to the Moon has not been a happy one. This has been a classic example of the scientific method of investigation: with the theorists on one side doing their best to model the motion and the observers on the other side testing every feeble attempt. The problem was that the model of the Moon's motion did not represent the longitude over more than a decade or so. This obvious lack was first noted by Laplace who stated there must be some gravitational effect lacking in the theories. It should be noted that to facilitate computations, the theories were reduced to the form of tables with the coefficients being adjusted to observations made over the recent past. The almanac maker then has to use those tables to predict the position of the Moon for a number of years in advance so that the resulting ephemeris can be used for comparison with observations and the determination of the observers' position. When, after several years, the observed position failed to agree with the predicted position, the observers would blame the theorists and vice versa, and the almanac maker had to sail between these two camps. The almanac maker then had to start over with a set of tables adjusted to more recent observations in hopes of being able to make a better prediction. Such was the case when Nevil Maskelyne, the fifth Astronomer Royal of Great Britain, first produced the British Nautical Almanac in 1767. For the position of the Moon he utilized Mayer's tables, but within the next thirty years was twice forced to readjust the coefficients of the tables by comparison with Bradley's observations of the Moon in order to maintain the required accuracy. By the late 1700's the savvy British navigator had learned to treat the ephemeris of the Moon with some caution. Donald Sadler, late Superintendent of Her Majesty's Nautical Almanac Office told

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the apocryphal story of a Spanish ship and a British ship meeting in mid-Atlantic at that time. The Spanish ship was laden with gold from the New World headed back to Spain. The British ship was headed westward to North America. In the exchange of amenities the Spanish captain sent over a small chest of gold to the British captain. The British captain, finding nothing else, sent over his only copy of the British Nautical Almanac. As the story goes the British ship made port safely and the Spanish ship was never heard from again.

The Work of Newcomb and Brown

With Laplace's dictum firmly in mind there followed a succession of theories each more complete gravitationally than its predecessor but with the same result; the observed longitude of the Moon drifted away from its tabular position as time went by. When the American Nautical Almanac office was founded on March 3, 1849 and located at Harvard University, preparations for the first volume of the American Ephemeris for 1855 were commenced. The ephemeris of the Moon was based upon tables Pierce derived from those of Airy which were fundamentally based on the theory of Plana with two Venus terms discovered by Hansen in 1847. In 1857, P. A. Hansen completed his theory of the Moon. The coefficients were adjusted to the observations from 1750 to 1855 and a good representation of the position of the Moon was realized. By 1869, however, the Moon was deviating from observations so greatly that Newcomb decided to take up the problem. At the time the Moon was falling behind its tabular place at a rate of over 1/2-second per year. His study had two objectives. First, find whether any unknown terms of long period could be derived from gravitational theory. Second, see what terms not included in the theory were shown to exist by all the observations. The observations to be discussed were meridian transits, and occultations of stars by the Moon, with ancient eclipses for information about the secular term. During the period from 1878 to 1888 all of the occultation observations from 1750 to 1880 were reduced but then the lunar problem was set aside because of necessary work on the planetary theories. After his retirement in 1897, Newcomb again took up his study of the theory of the Moon under the auspices of the Carnegie Institution. He found that the observations seemed to show a term in the Moon's mean longitude with a period of nearly three centuries and a coefficient of 10 seconds of arc not explained by gravitational theory. He labeled this "the Fluctuation". Newcomb concluded that "So long as "the fluctuations" might be supposed to arise from defects in the computations of

gravitational theory we might plausibly suppose them to arise from actual periodic terms which had eluded our scrutiny. But today it seems almost as certain as any proposition in mathematical science can be that there are no known masses of matter the gravitational action of which could produce the observed effects". The dictum of LaPlace was finally laid to rest. E. W. Brown when generating his extensive theory of the motion of the Moon, concurred with Newcomb regarding the fluctuations. Brown's theory of 1919 became the basis of the lunar ephemeris in the American Ephemeris from 1923 to 1959. The mysterious discrepancy between gravitational theory and the actual motion in longitude of the Moon was compensated for by the great empirical term.

G. M. Clemence and a New Time Scale

With the rejection by Newcomb and Brown of the idea that the fluctuation could arise from some neglected gravitational source, de Sitter turned his attention to an investigation of how a variation in the Earth's rotation might be reflected in the longitudes of the planets and the Moon. Harold Spencer Jones followed up on this idea with an analysis of the Greenwich Observatory observations of Mercury and Venus and the Moon and found evidence that the source of the entire problem lay with the variable rate of rotation of the Earth. Up to this time all the theorists had regarded time given by the rotation of the Earth to be the equivalent of the argument of the dynamical theories. On the basis of Spencer Jones work it became apparent that mean solar time was not an invariable time scale as had been assumed in the past. In 1950 Gerald Clemence made a proposal for a new time scale called ephemeris time based on the sidereal period of the Earth's orbit which was supposed to be the same as the independent argument of the dynamical theories of the Sun, Moon and planets. In 1952, the International Astronomical Union adopted Clemence's suggestion with the statement that "In all cases where the mean solar second is unsatisfactory as a unit of time by reason of its variability the unit adopted should be the sidereal year of 1900.0, that the time reckoned in these units be designated ephemeris time". The difference between the two time scales was designated ΔT which equaled ephemeris time minus universal time. As thus defined ephemeris time fulfills the requirement of a uniform time scale independent of the variations in the speed of the Earth's rotation. Further, to bring the lunar ephemeris into accordance with the solar ephemeris it was recommended that Brown's tables of the motion of the Moon should be amended by removing the empirical term and applying a small correction to bring the

longitude of the Moon into agreement with the longitude of the Sun. The Improved Lunar Ephemeris (1952-1983) was calculated directly from the trigonometrical series on which Brown based his tables, under the direction of Wallace Eckert, former director of the Nautical Almanac Office as a demonstration of the Selective Sequence Electronic Calculator of the International Business Machines Company in January of 1948. The resulting ephemeris was strictly in accord with gravitational theory and it allowed the direct determination of the correction ΔT by comparison with observations. Evaluating Brown's trigonometrical series directly gave an increased accuracy in the ephemeris of .001 seconds of time in right ascension and 0.01 seconds of arc in declination. The years 1952-59 were published separately and in 1960 this became the basis for the ephemeris of the Moon printed in the American Ephemeris and the British Astronomical Ephemeris. The increase in accuracy of the lunar ephemeris was well warranted to meet the corresponding increase in observational accuracy. C. B. Watts' addition of a traveling wire micrometer with photographic registration to the six-inch transit circle produced a long series of very good observations. This was repeated in his design of the seven-inch transit circle. Observations of occultations of stars by the Moon were improved in accuracy by Watts' charts of the marginal zone of the Moon. These charts were refined by the extensive occultation program conducted by David Dunham and Tom van Flandern. Better star positions and modern-timing techniques also improved the occultation data.

Wallace Eckert and the Moon

Wallace Eckert who served as director of the Nautical Almanac Office during the period of 1940 to 1945, had worked with E. W. Brown during the 1930's on an elaboration of Brown's theory. He again turned his attention to the Lunar Theory in the 1950's when the rapid development in speed and capacity of computing machines made a solution by Airy's method more tractable. The solution of the main problem of the Lunar Theory by the method of Airy authored by Eckert and Harry F. Smith, Jr. appeared shortly after Eckert's untimely death in 1971. The theory was brought to completion in 1986 by Martin C. Gutzwiller and Dieter S. Schmidt and stands as a monument to Eckert's lifelong fascination with the lunar problem.

The Birth of Lunar Laser Ranging (LLR)

Long range rocket development during World War II led to the program of artificial Earth satellites during the International Geophysical Year (July 1957-December 1958). Transmitters on board allowed determination of the positions of these artificial Earth satellites. With the invention of the laser, procedures similar to those used with microwave radar were modified to provide optical range measurements with great precision and accuracy. The first experiments to obtain the flight time of a laser beam to an Earth satellite and return were made at the NASA Goddard Space Flight Center in the mid-nineteen sixties. The idea of receiving laser light returns from the Moon's surface went more or less in parallel with the artificial Earth satellite experiments. The problem with the Moon was the spreading of the beam of outgoing laser light as it was reflected by the rough lunar surface which made precise distance measurements, as could be done with artificial Earth satellites, impossible. Some of these lunar experiments were made in the 1960's at MIT and in Soviet Russia but with little success. In the face of this failure it was seen that a corner retro-reflector on the lunar surface was a necessity. With the birth of the NASA Apollo Project in the late 1960's the concept of laser ranging to a corner reflector package placed on the surface of the Moon became a reality. The deployment of such a retro-reflector package, was accomplished during the Apollo 11 mission in July 1969; and at long last lunar laser ranging became possible. Other retro-reflector packages were placed on the surface of the Moon during the Apollo 14 mission in January of 1971 and the Apollo 15 mission of July 1971. In addition, two retro-reflector packages built by the French were placed on the lunar surface by Soviet landers. The first lunar laser ranging observations of the Apollo 11 retro-reflector package were made with the 3.1-meter telescope at the Lick Observatory in 1969. The ranging system at Lick was designed for quick acquisition only and not for an extended program. Early lunar laser range measurements were made by the Air Force Cambridge Research Laboratories Lunar Ranging Observatory in Arizona in 1969, the Pic du Midi Observatory in France in 1970 and the Tokyo Astronomical Observatory in 1972. In the following decades, lunar laser ranges were also accomplished at Maui in the Hawaiian Islands, the Soviet Union, Australia and Germany. Continuous lunar laser ranging programs have been carried out at the McDonald Observatory in the United States and the CERGA Observatory in France.

The McDonald Observatory LLR Station

With scheduling for placement of a retro-reflector package on the surface of the Moon by Apollo 11, a suitable observing site had to be selected. More than an optical telescope is necessary in forming an observing station. It requires a powerful laser, a high-speed computer and an accurate timing system. Plans had originally been made for an observing facility on the top of Mount Haleakala on the island of Maui. But it was found in the latter stages of planning for the Apollo mission that the required changes at the Hawaii site would make it impossible to put in place the necessary equipment and modifications as well as test the system in time to be operational for the Apollo 11 landing. A new 2.7-meter reflecting telescope at the McDonald Observatory located in West Texas had just become operational. The Lunar Ranging Experiment (LURE) team approached Dr. Harlan J. Smith, director of the observatory, regarding a commitment to long-term lunar laser ranging. The telescope had been largely funded by NASA in connection with a major planetary observation program. The additional equipment to perform the LLR experiment was obtained and the results were outstanding. The 2.7-meter system of the McDonald Observatory became the principal LLR station of the 1970's and the early 1980's. It used a korad ruby laser and routinely produced LLR normal point data with an accuracy in the range of ten to fifteen centimeters. Following a decade-and-a-half of continuous LLR operations at McDonald Observatory, the 2.7 meter ranging system was shut down; partly because it could not observe artificial Earth satellites as well as the Moon and because it was limiting access to the 2.7 meter telescope for other observing programs. The program was taken up again by a specially designed 0.76-meter telescope which allowed rapid sluing motion for observing artificial Earth satellites but could be used as well for observing the Moon. This new system was built around a frequency doubled neodymium YAG laser and produced LLR data approaching one centimeter normal point accuracy. The objectives of the new observing system were: (a) to provide for a continuing program of LLR observations at McDonald Observatory without requiring access to the 2.7 meter telescope; (b) take advantage of 15 years of progress in electronic computer technology and laser timing to create a much more accurate station; (c) to reduce the cost of McDonald LLR activity with a more highly automated system; (d) to provide both lunar and artificial satellite observations close to one node of the National Geodetic Survey/International Radio Interferometric Surveying Network, permitting efficient comparisons between the lunar and radio interferometric

techniques. This new observing station was positioned in the saddle between Mount Lock and Mount Fowlkes and preliminary operations began in the summer of 1983. However, the saddle site proved to be a poor observing location because of the velocity of the winds blowing through the saddle which created difficult seeing conditions and some questions with regard to the stability of the telescopes concrete support pad. A new site on top of Mount Fowlkes was developed and the instrument and all associated equipment were moved to that site in February 1988 where it has operated to the present time. The new more precise observational data obtained with laser ranging to the Moon now required a higher standard ephemeris for comparison. Because of the availability of large capacity and very fast computing equipment, the general perturbation theories of the past were replaced by numerical integrations of the equations of motion. LLR data are being provided continuously now by only two stations, McDonald Observatory in the United States and the CERGA Observatory in France.

Thirty Years of LLR Data on the Moon

The LLR data that have been gathered now for 30 years are vital to the construction of astronomical almanacs. Of most relevance, the LLR data set provides a dramatic improvement, compared to classical optical data, in the accuracy with which the lunar orbit can be known. The lunar orbit orientation is determined at least two orders of magnitude more accurately and the radial component is determined at least four orders of magnitude more accurately, through the use of LLR data. In fact, the radial distance variations are determined slightly better than the present 1-2 cm LLR range accuracy and the angular rate uncertainty is no more than 0.3 milliseconds of arc per year.

Related LLR Results

Beyond their direct relevance to the construction of almanacs, the LLR data contribute in other, perhaps less direct, ways. Among these are solid Earth sciences, geodesy and geodynamics, terrestrial and celestial fundamental reference frames, lunar physics, general relativity, and gravitational theory. The LLR data contribute to our knowledge of the precession of the Earth's spin axis, the lunar induced nutation, polar motion and Earth rotation, the determination of the Earth's obliquity to the ecliptic, the intersection of the celestial equator and the ecliptic (i.e., the equinox), lunar and solar solid body tides, lunar tidal deceleration, lunar physical and free librations, and energy dissipation in the lunar interior.

They provide vital input into the lunar surface cartographic and surveying system. They determine Earth station and lunar surface retro-reflector location and motion, the Earth-Moon mass ratio, lunar and terrestrial gravity harmonics and Love numbers, relativistic geodesic precession, and the strong equivalence principle of general relativity.

Looking to the Future

A tremendous amount of basic science has been accomplished using LLR data over the past 30 or so years, above and beyond that necessary for the compilation of almanacs. Because of the passive nature of the lunar reflectors and the steady improvement in equipment, the LLR data will continue to provide for state-of-the-art results in many astronomical disciplines well into the future. Similar to other astrometric techniques, the LLR experiment is broad ranging in results and its gains are steady, as its database continues to expand. The contributions of LLR to the construction of lunar almanacs will continue for many years to come.

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OBSERVATIONS IN PLANETARY EPHEMERIDES

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Introduction

Since not everyone who will read these proceedings is an astronomer, I want to give a layman's guide to observations in ephemerides.

Before I talk about observations in ephemerides, I will answer two questions. What is an ephemeris? What role do observations play in making an ephemeris? I will then discuss properties common to all observations, and the two major types of observations found in planetary ephemerides. I will finish with a quick look at how observations may develop over the next twenty to thirty years.

What is an Ephemeris?

An ephemeris is just a table telling you where something is at a given time. If you have ever used a train timetable like Figure 1, you have used an ephemeris.

New York ... Newark ... Metropark ... Philadelphia ... Wilmington ... Baltimore ... New Carrollton ... Washington														
Monday through Friday Service (week-end not operated for Trains 101 and 115)														
Train Number	201	101	103	105	107	109	111	113	115	117	119	121	123	125
New York, NY	6:25A	6:55A	7:05A	7:15A	7:25A	7:35A	7:45A	7:55A	8:05A	8:15A	8:25A	8:35A	8:45A	8:55A
Newark, NJ	6:35A	7:05A	7:15A	7:25A	7:35A	7:45A	7:55A	8:05A	8:15A	8:25A	8:35A	8:45A	8:55A	9:05A
Metropark, NJ	6:45A	7:15A	7:25A	7:35A	7:45A	7:55A	8:05A	8:15A	8:25A	8:35A	8:45A	8:55A	9:05A	9:15A
Philadelphia, PA	6:55A	7:25A	7:35A	7:45A	7:55A	8:05A	8:15A	8:25A	8:35A	8:45A	8:55A	9:05A	9:15A	9:25A
Wilmington, DE	7:05A	7:35A	7:45A	7:55A	8:05A	8:15A	8:25A	8:35A	8:45A	8:55A	9:05A	9:15A	9:25A	9:35A
Baltimore, MD	7:15A	7:45A	7:55A	8:05A	8:15A	8:25A	8:35A	8:45A	8:55A	9:05A	9:15A	9:25A	9:35A	9:45A
New Carrollton, MD	7:25A	7:55A	8:05A	8:15A	8:25A	8:35A	8:45A	8:55A	9:05A	9:15A	9:25A	9:35A	9:45A	9:55A
Washington, DC	7:35A	8:05A	8:15A	8:25A	8:35A	8:45A	8:55A	9:05A	9:15A	9:25A	9:35A	9:45A	9:55A	10:05A

Weekend Service														
Train Number	205	207	209	211	215	217	219	221	223	225	227			
New York, NY	6:30A	6:40A	6:50A	7:00A	7:10A	7:20A	7:30A	7:40A	7:50A	8:00A	8:10A			
Newark, NJ	6:40A	6:50A	7:00A	7:10A	7:20A	7:30A	7:40A	7:50A	8:00A	8:10A	8:20A			
Metropark, NJ	6:50A	7:00A	7:10A	7:20A	7:30A	7:40A	7:50A	8:00A	8:10A	8:20A	8:30A			
Philadelphia, PA	7:00A	7:10A	7:20A	7:30A	7:40A	7:50A	8:00A	8:10A	8:20A	8:30A	8:40A			
Wilmington, DE	7:10A	7:20A	7:30A	7:40A	7:50A	8:00A	8:10A	8:20A	8:30A	8:40A	8:50A			
Baltimore, MD	7:20A	7:30A	7:40A	7:50A	8:00A	8:10A	8:20A	8:30A	8:40A	8:50A	9:00A			
New Carrollton, MD	7:30A	7:40A	7:50A	8:00A	8:10A	8:20A	8:30A	8:40A	8:50A	9:00A	9:10A			
Washington, DC	7:40A	7:50A	8:00A	8:10A	8:20A	8:30A	8:40A	8:50A	9:00A	9:10A	9:20A			

HOLIDAY SERVICE NOTE														
A special schedule will operate Nov. 24-25, 1998 and Dec. 21, 1998-Jan. 1, 1999. Consult the train schedule for specific schedules in effect during these periods. No Club Class Service on Dec. 25 or Jan. 1.														

Figure 1: A train timetable is an example of an ephemeris.

A planetary ephemeris is the same sort of thing. The only differences between a planetary ephemeris and a timetable are that the planetary ephemeris is three-dimensional rather than one-dimensional and it usually includes the planets' velocities as well as their positions.

Newcomb is a project to produce high precision ephemerides of solar system objects including the planets, the Moon, asteroids, and possibly the

natural satellites of planets. These ephemerides will be used to provide some of the basic research needed to maintain and improve the products of the Nautical Almanac Office and the Astronomical Applications Department.

To produce a planetary ephemeris you need two equally important ingredients: a mathematical model and observations of the planets.

A mathematical model is a set of equations that allow me to make predictions from bits of information. For example, let us say that I have a car that travels 60 miles per hour in a straight line and I want to know how far I will travel from 7:00 to 10:00 in the morning. My mathematical model would be:

$$\begin{aligned}\text{distance} &= \text{speed} \times (\text{ending time} - \text{beginning time}) \\ &= 60 \text{ miles per hour} \times (10:00 - 7:00) \\ &= 60 \text{ miles per hour} \times (3 \text{ hours}) \\ &= 180 \text{ miles}\end{aligned}$$

For an ephemeris project, such as Newcomb, the model consists of elements such as the masses of the planets and larger asteroids, their initial positions and velocities, and numerous other parameters that describe the physics of the motions of the planets and link the positions that we observe with the positions as calculated in the ephemeris.

Observations

Observations provide the information needed to design a correct model.

In the example above, how do I know my speed? How do I know what time I started and stopped? Probably I looked at the speedometer in my car and glanced at my watch when I started and stopped. These are examples of observations.

Observations are not perfect. They generally contain two types of errors: random errors and systematic errors.

A random error occurs because the measuring device is not perfect. Going back to driving my car, after driving for three hours I look at my odometer and rather than saying that I have gone 180 miles it says I have gone 179.5 miles. If I start out again at 60 miles per hour, three hours later my odometer might read 180.1 miles. What is going on here? There is

some random factor that is causing small errors in my measurement. Each time I make the measurement I might come out with a slightly different distance. The source of the error may be something simple, like I do not have a second hand on my watch so I can only tell time to the nearest minute. At 60 miles per hour, I move a mile in a minute. Not having a second hand means I can have errors of several tenths of a mile. However, the error is just as likely to be too large as it is to be too small. Thus, if I repeat the measurement several times, the average value measured will be very close to the actual value.

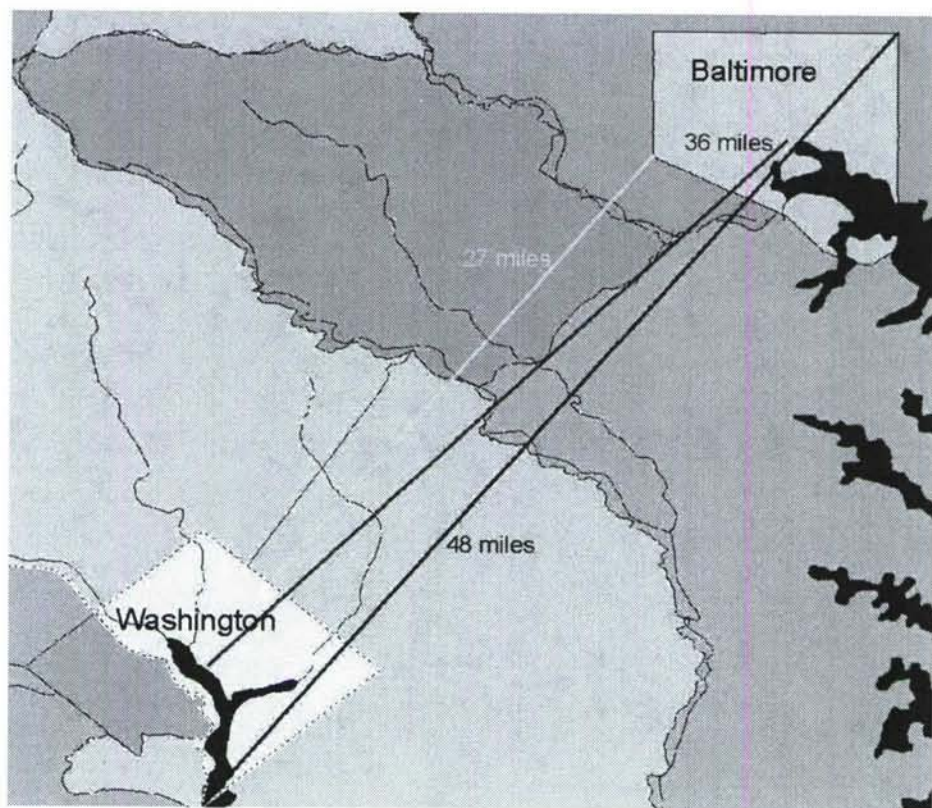


Figure 2: The uncertainty in the distance from Washington, DC to Baltimore, MD.

Systematic errors, however, are harder to handle. This type of error is caused by having an error in the *way* the observation is made. For example, if the odometer in my car measures kilometers and I think that it measures miles, I would make a systematic error. If I was traveling at 60 miles per hour the odometer would read 96 rather than 60 after one hour.

No matter how many times I make this measurement, I will get a similar number every time. The only way to correct this mistake is to calibrate my method of making observations. That is I test my measuring device to determine what unit I am using to make observations. In this example, I can use my watch and speedometer to determine that when my odometer reads 96 I have actually gone 60 miles.

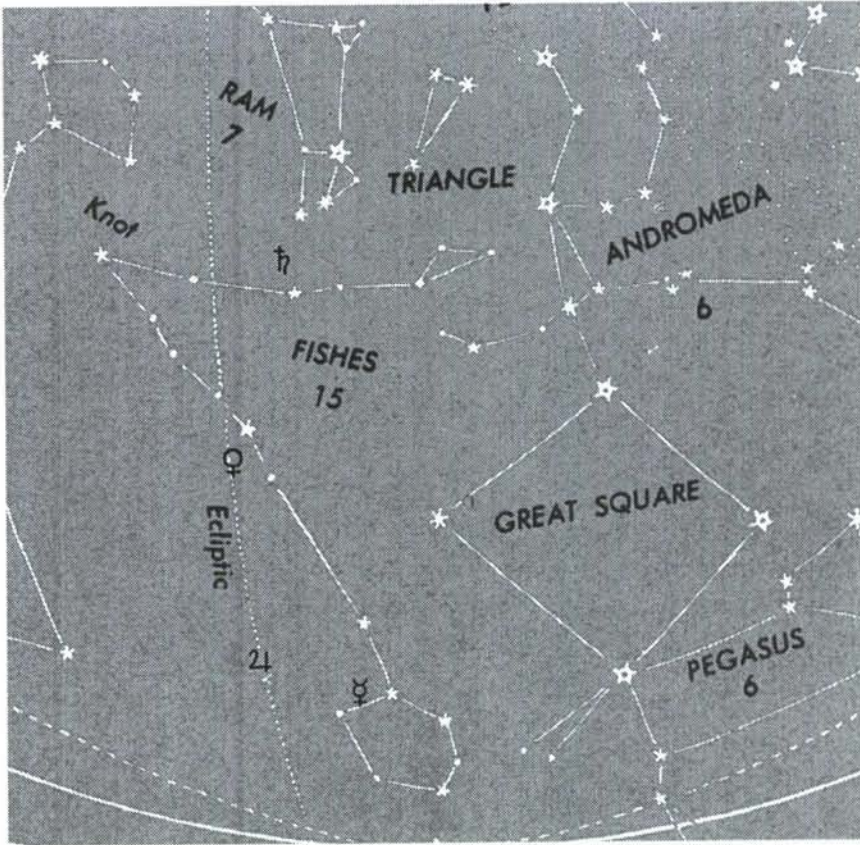


Figure 3: An example of a sky map.

In making an observation you also have to be careful to define exactly what it is you are measuring. For example, how far is it from Washington, DC to Baltimore, MD? If I measure from city center to city center as shown in Figure 2, the distance is 36 miles. But if I measure from the closest point on each border, the distance is only 27 miles and if I measure from the farthest corner of each city the distance is 48 miles.

Usually, I want the distance from city center to city center. Where is that? What is the center of a city? Let us define city hall as the city center. City hall, however, does not have to be at the physical center of the city. Now I have to find city hall. If I have a map that shows where city hall is I could use that. Figure 2, however, does not show where the city halls are. The cities are extended objects, that is they are not just points but cover an area on the map. Accurately finding where the city hall is within the city is difficult because what I am looking for is hidden within the blank area of the city.

For a planetary ephemeris the center I want to observe is the center of mass of the planet, but like the city halls above, it is buried within the body of the planet. Also, like city hall it does not have to be at the physical center of the planet. Usually, it is very close to the physical center, but in the case of Mars it is offset by about 900 yards. This may sound like a small difference, but if it was ignored, the accuracy of the ephemeris of Mars would be 100 times less than the best current Martian ephemeris.

All planetary ephemeris observations break down into two types: plane-of-sky (angle) observations and time delay-Doppler (distance-speed) observations.

Plane-of-Sky Observations

A plane-of-sky observation is the same as finding where something is on a map of the sky. For example, Figure 3 shows a map of the western sky for 7:00PM March 5, 1999. On the map are the planets Mercury, Venus, Jupiter, and Saturn in the constellation of Pisces. Like a map, each point on the sky has a pair of coordinates, an address, so we can refer to the planet's position rather than having to draw the map to show where it is.

Plane-of-sky observations are the oldest existing observations of the sky. They can be made with the naked eye. We have records of this type of observation among the writings of the Sumerians and ancient Chinese. Using the best techniques presently available our best plane-of-sky observations are 100 times better than those made 200 years ago, and 20,000 times better than those made by our ancient ancestors. The astrometric satellite FAME promises to increase the best accuracy available by another factor of ten! On a large scale, the sky does not appear as a plane, but as a sphere that we are at the center of, so our plane-of-sky map is more like the interior surface of a globe than a flat surface. Like a globe, the most

convenient units to use for mapping points are angular units. When we refer to the accuracy of a position we use angular units like degree, arcminute, and arcsecond.

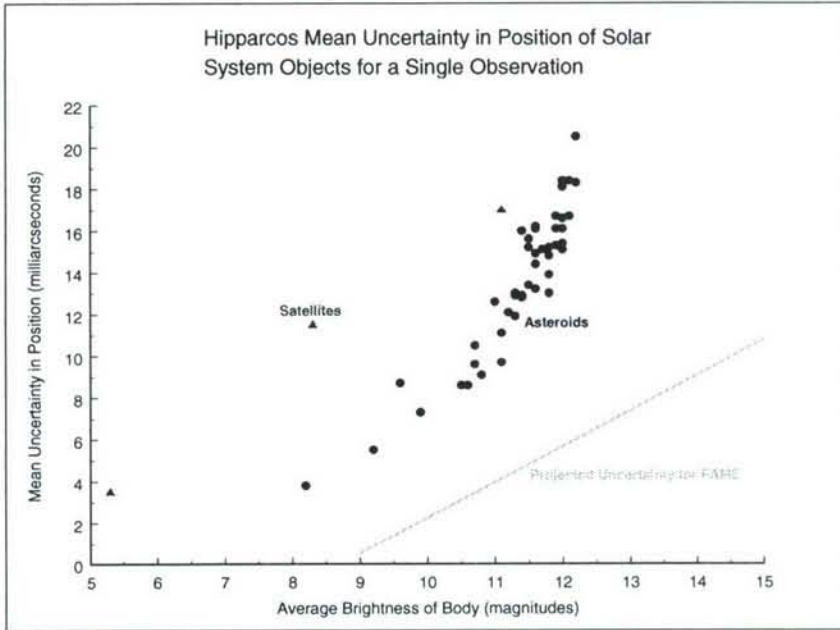


Figure 4: The mean uncertainty in position as a function of brightness for solar system bodies observed by Hipparcos.

How good are plane-of-sky observations? Figure 4 shows the observations made by Hipparcos, a spacecraft designed to make high accuracy optical measurements of the stars. Hipparcos observed some of the asteroids and satellites of the planets along with the stars.² The accuracy depends on how bright the object is. The best single observation positions have an accuracy of 2/1000 of an arcsecond.

However, observing the position of a planet is more difficult than it is for a point object like a star or asteroid for several reasons. Planets, like a city, are extended objects. They have visible disks when you look at them through a telescope rather than appearing as points of light, like a star. Except for Mercury and the Moon, they all have atmospheres which means that their edges are fuzzy. The Moon is so close that its edge does not

appear smooth but lumpy because of mountain ranges and crater rims near the edge of the disk. Jupiter and Saturn rotate so fast that they appear to be elliptical rather than circular. Saturn's rings may be beautiful to look at, but they make it difficult to observe its position. Mercury, Venus, the Moon, and, to a lesser extent, the other planets go through phases because we see only part of the illuminated surface (Figure 5). All of these effects lead to both random and systematic errors in observing the position of a planet. The absolute best optical plane-of-sky observations of the planets have uncertainties of about a tenth of an arcsecond.

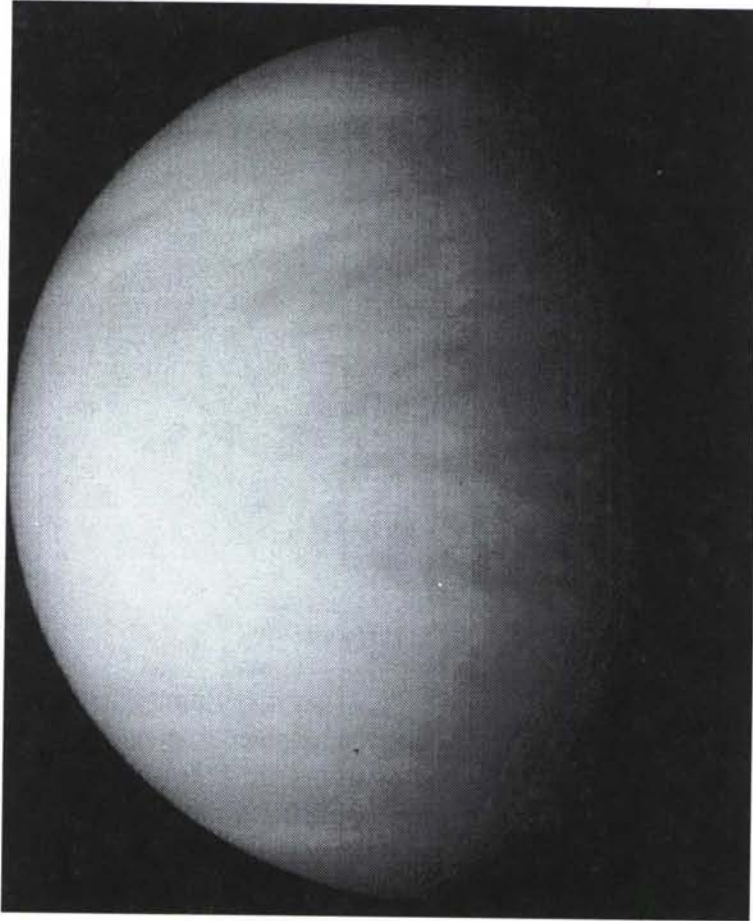


Figure 5: Venus, like Mercury, the Moon, and Mars has phases that make it difficult to determine its position.

An arcsecond is equal to $1/3600$ of a degree. This is a very small angle. For example, the circle that makes up the Naval Observatory is 1000 feet in radius (Figure 6). If you were to walk all the way around the perimeter, you would walk about 6283 feet, over one nautical mile. Viewed from the center of the observatory, an arcsecond along the circle that forms this perimeter is only $1/16$ of an inch!



Figure 6: The U.S. Naval Observatory is on a circular plot of land 1000 feet in radius.

Now you are probably wondering, "Does anything ever have to be that accurate?" The answer is, "This is not nearly accurate enough."

Like a map, plane-of-sky observations are two-dimensional. They do not include the distance from the observer to the object. Just like a landscape is projected onto a flat canvas, planets and stars are projected onto the plane-of-sky.

The distance to an object is important in converting from the angular unit of measure of a plane-of-sky observation to the linear unit of measure of an ephemeris. The farther away an object is the larger the uncertainty in the linear position for a given uncertainty in its angular position. That is,

an object that is farther away from us needs to move a greater linear distance to have the same angular change in position. Figure 7 shows the linear uncertainty in position, in miles, for an observation of each of the planets at its closest approach to the Earth for an observed angular uncertainty of one arcsecond. The Moon is so close to the Earth that the linear uncertainty is only one mile while the linear uncertainty in the position of Neptune is never less than 19,000 miles. Thus when talking about something at the distance of Neptune, an arcsecond is the equivalent of ten times the distance from Washington, to Los Angeles.

Take the recent Mars Pathfinder mission. It had to hit a spot on the surface of Mars 450 yards across. If you were a marksman on the Earth, to hit this target you have to be accurate to $1/10,000$ of an arcsecond. Fortunately, Mars Pathfinder could make in-flight corrections. The size of these corrections had to be small because the amount of fuel available was limited. Including in-flight corrections, Mars Pathfinder only had to be accurate to $1/100$ of an arcsecond.³

Hitting this target would be ten times more difficult than anything Natty Bumppo⁴ ever did. However, it is child's play once you consider the additional complications that were needed to get Mars Pathfinder to its target on Mars.

First, both the Earth and Mars wobble on their axes.

Second, the orbits of the Earth and Mars around the Sun are not circular, but elliptical and the speed at which each planet moves changes depending on its distance from the Sun.

Third, not only does the Earth's gravity hold us down on its surface, but it reaches out across the solar system and tugs on Mars, so Mars does not follow the orbit that it would if it were circling the Sun by itself. In addition to the Earth and Mars, every body in the solar system has a gravitational effect on every other body. To determine the motion of Mars well enough for Mars Pathfinder to hit its target, not only was the gravitational pull of all the planets included, but the gravitational pull of the Moon, and 300 of the largest asteroids were included as well⁵

With all the uncertainty in the observations how is it possible to produce a high accuracy ephemeris? There are at least four things that can be done.

First, many observations taken over a long period of time will reduce the uncertainty in the ephemeris. This is the traditional way of achieving higher accuracy. Recently, I produced a set of ephemerides for fifteen of

the largest asteroids.⁶ On average, each asteroid had 4000 observations covering 150 years. The average uncertainty in the observations was 3 arcseconds. The uncertainty in the position of the asteroids in the final ephemerides ranged from 1/15 to 1/60 of the uncertainty in the average observation.

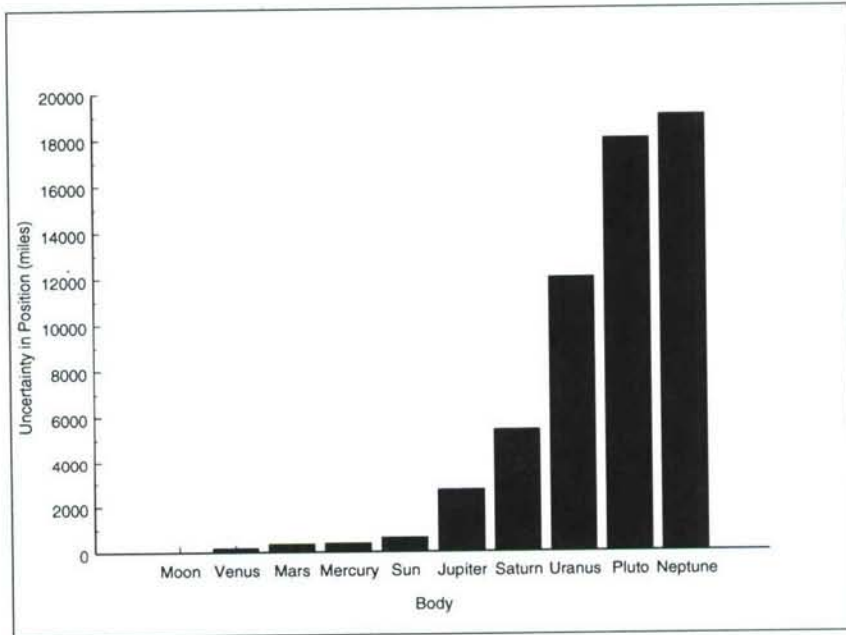


Figure 7: The linear uncertainty for an optical plane-of-sky observation of each of the planets at closest approach with an angular uncertainty of one arcsecond.

Second, observe the satellites of the planets rather than the planets themselves. The advantage in observing the satellites of the planets is that they appear as points on the sky. Thus we get rid of all of the complications that make the accuracy of the positions of the planets a factor of about 300 worse than the accuracy of the best positions of the stars. Hipparcos, which has produced the most accurate optical plane-of-sky observations to date², observed the brightest satellites of Jupiter and Saturn. The astrometric satellite FAME is designed to produce individual observations ten times more accurate than Hipparcos and will be able to observe the brightest satellites of Mars, Jupiter, Saturn, Uranus, and Neptune.^{1,7}

However, to find the ephemeris of a planet from observations of its satellites you need to determine the ephemerides of the satellites as well. Thus, the model for producing the planet ephemeris must be more complex. Also, not all planets have satellites.

Third, use Very Long Baseline Interferometry (VLBI) to make observations. This works by taking observations at two or more radio telescopes separated by long distances, sometimes by as much as the diameter of the Earth. These observations are combined to produce very high accuracy position observations of an object. These observations are about 100 times more accurate than the most accurate optical plane-of-sky observations. However, to make these observations you need a small, powerful radio source on or near the planet. The only sources that fit this requirement are spacecraft. Therefore, you need spacecraft like Galileo or Magellan circling a planet. Just like observing the satellites of a planet, you now need to include the orbit of the spacecraft around the planet. VLBI is also expensive. Because of these restrictions, only a couple dozen VLBI observations of the planets exist even though they are very accurate.

Fourth, you can make time delay-Doppler (distance-speed) observations rather than plane-of-sky observations.

Time delay-Doppler Observations

Time delay or distance observations are made by sending out a pulse of light or radio waves from a source, such as a radar or laser. This pulse is reflected off a body and received back at its source. Since the speed of light is constant, the length of time it takes to make the round trip tells you how far away the body is. Figure 8 gives an example of distance observations using a radio telescope.

Also, if the body is moving towards us, it will "crowd together" the light or radio waves by reflecting each wave crest a little sooner than expected. Conversely, if the body is moving away from us the time between each wave crest being reflected off the planet is a little later than expected. This allows us to find the speed at which the body is moving either towards or away from us by comparing the wavelength that was sent out with the one that is returned to the observer. This is called the Doppler⁸ effect, and is how radar guns detect the speed of an automobile or baseball.

The great advantage of time delay-Doppler observations is that they are very accurate, especially if you know exactly where the pulse is being reflected from on the surface of the body. The distance from the Earth to

the Moon can be measured with an uncertainty of less than an inch because we can use lasers to bounce light pulses off reflectors left on the Moon by the astronauts. This is called Lunar Laser Ranging. We were able to do nearly as well with Mars using radio waves and the transponders on the Mars Viking landers and the Mars Pathfinder spacecraft to act like reflectors. These gave the distance to Mars to an uncertainty of only 11 yards over more than 48,000,000 miles! Even without a known reflector the distances to the surfaces of Mercury and Venus is measured with an uncertainty of less than 1 mile.

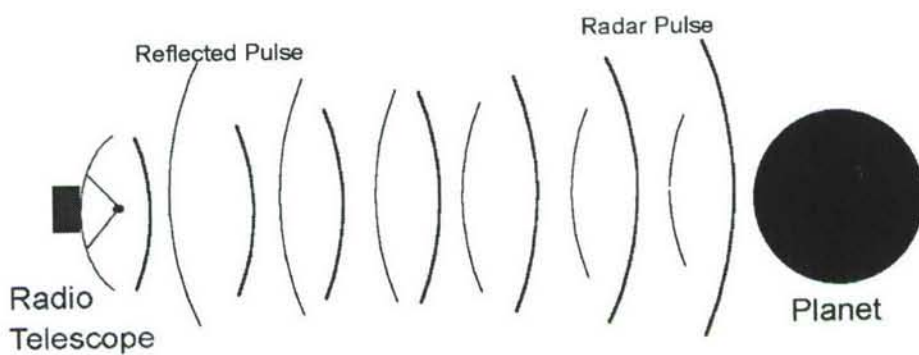


Figure 8: Bouncing a radar pulse off a planet is an example of a time delay observation.

Time delay-Doppler observations have two drawbacks. First, you need a surface that will reflect the pulse. This means that while lots of observations have been made of Mercury, Venus, Mars, and the Moon we can not get pulses returned from the giant planets like Jupiter and Saturn because they absorb the radio waves rather than reflecting them. These, of course, are the planets from which we most want time delay-Doppler observations because they are so distant that their plane-of-sky observations have the largest linear uncertainties.

The second drawback is that it takes a lot of energy in the pulse sent out to receive an observable return signal. The farther away an object is or the smaller an object is the fainter its return signal. If two objects are the same distance away, but one is only $\frac{1}{2}$ the size of the other, the strength of the reflected signal from the larger object will be four times greater than from the smaller object. If two objects are the same size but one is twice as far away the signal strength from the nearer object will be 16 times greater.

To date, the most distant objects to have time delay observations made are two observations each of Ganymede and Callisto, two of the large satellites of Jupiter.⁹

Future Observations

Although optical plane-of-sky observations will probably never be as accurate as time delay-Doppler observations, they will continue to play a dominant role in the ephemeris observations of the outer planets for as long as other observation types remain relatively rare. Better ephemerides of the satellites of the outer planets and better methods of observation will probably increase the use of optical observations of the planets' satellites as a method of improving the ephemerides of the planets.

VLBI and time delay-Doppler observations of spacecraft on or near other planets will most likely continue to be the most accurate observations that can be made. However, these observations will remain rare because the cost of launching and observing these interplanetary spacecraft is high. The next new source of spacecraft observations will be from the Cassini spacecraft that is currently on its way to Saturn.

Time delay observations of objects farther out in the solar system may be made in the near future. Radar observations have been made of Titan, the largest satellite of Saturn,¹⁰ but the return signal was too weak to be used in determining the distance using the time delay. However, a recent upgrade to the Arecibo radio telescope,¹¹ may make radar ranging to Titan feasible.

The orbit of the Moon is known to within a fraction of a yard, thanks to Lunar Laser Ranging. Until we have better models dealing with the effects of the interior structure of the Earth and Moon and the effect of the asteroids on the Moon's orbit, it is unlikely that we will be able to improve significantly on the ephemeris of the Moon. However, the inadequacies in the model for the orbit of the Moon also mean that Lunar Laser Ranging needs to continue to maintain the present accuracy of the ephemeris.

Knowing the position of the Moon to a fraction of a yard may sound excessively precise. However, as man moves away from the Earth, high accuracy ephemerides are a necessity to finding his way around the solar system and will be necessary when man returns to the Moon.

NOTES

1. Phillips, J.D. 1999, *The Fame Error Budget*, draft Memo gives the single observation uncertainty of 0.00055 arcseconds at magnitude 9 and 0.0108 at magnitude 15.
2. European Space Agency, FAST, NDAC, TDAC, & INCA 1997, The Hipparcos and Tycho Catalogues, Volume 10, show the mean single observation uncertainty for solar system objects 0.004 arcseconds at magnitude 8.2, 0.006 arcseconds at magnitude 9.2, and 0.019 arcseconds at magnitude 12.2.
3. The accuracy of Mars Pathfinder was determined from trajectory correction maneuver (TCM) information by R. Vaughan, Mars Pathfinder Navigator given at <http://mars.jpl.nasa.gov/MPF/mpf/mpfnvpr.html>.
4. Natty Bumpo, the protagonist in several James Fenimore Cooper books, is renowned for his outrageous marksmanship.
5. Standish, E.M., Newhall, X X, Williams, J.G., & Folkner 1995, JPL Planetary and Lunar Ephemerides, DE403/LE403, Jet Propulsion Laboratory Interoffice Memorandum, IOM 314.10-127.
6. Hilton, J.L. 1999, *U.S. Naval Observatory Ephemerides of the Largest Asteroids*, *Astron. J.*, **117**, 1077-1086.
7. Nautical Almanac Office, U.S. Naval Observatory, *Astronomical Almanac*, pp. F3 shows that Mars has two satellites with mean apparent magnitudes less than 15, Jupiter six satellites, Saturn seven, Uranus four, and Neptune one.
8. The Doppler effect was named for Christian Doppler who first analyzed the effect in 1842 using musicians on moving railroad cars.
9. Harmon, J.K., Ostro, S.J., Chandler, J.F., & Hudson, R.F. 1994, *Radar Ranging to Ganymede and Callisto*, *Astron. J.*, **107**, 1175-1181
10. Muhleman, D.O., Grossman, A.W., Butler, B.J., & Slade, M.A. 1990, *Radar Reflectivity of Titan*, *Science*, **248**, 975-980
11. Ostro, S.J. 1993, *Planetary Radar Astronomy*, *Reviews of Modern Physics*, **65**, 1235-1279

MODELING PLANETARY MOTIONS: WHY WE CARE AND HOW WE DO IT

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1. INTRODUCTION

1.1. Why do we need precise planetary positions?

There are several good reasons why we need precise planetary positions. I will mention just a few that impact the U.S. Naval Observatory and its various scientific (and military) programs and objectives. There are two broad requirement categories: Department of Defense (DoD) requirements and astronomical requirements, which overlap significantly. First, for ordnance guiding and targeting purposes, the DoD requires stellar positions to better than 20 milliarcseconds (mas)¹. Placing accuracy requirements upon a stellar reference frame has implications for how accurately we must then know, among other things, the positions of the planets and other solar system objects. The sequence of connections that joins the two seemingly disparate accuracies (that of the stars and that of the planets) requires a discussion of dynamical and astronomical reference frames, which I will get to in a moment.

The second broad requirement category is the astronomical need for accurate planetary positions. Besides the intrinsic interest of astronomers in planetary, asteroidal, and cometary positions, knowledge of these positions over time — called an *ephemeris* — fundamentally affects many areas of solar system and even stellar astronomy:

1. To the general public, perhaps the most apparent astronomical need for precise planetary positions is in spacecraft navigation.
2. Solar system celestial mechanics depends greatly on accurate positions. Theories of planetary and satellite motions live or die according to how well their predictions agree with observational knowledge of positions. These theories are the means by which we develop our most fundamental understanding of the many complicated dynamical processes and interactions in the solar system.

3. Another area where accurate knowledge of planetary positions is crucial is stellar occultations. If a planet is passing in front of a star, and we can predict where on the Earth's surface this event is visible, then we may learn several things, including density and composition of the planetary atmosphere, certain facts about the atmosphere of the occulted star, and, of course, better knowledge of either the star's position, the planet's position, or both. Further, if the occulting body is an asteroid, we can even determine the projected shape of the asteroid.
4. Finally, General Relativity has been tested by observing starlight that grazes a body — the Sun, Jupiter, and Earth have all been used thus. Again, accurate knowledge of planetary positions is essential.

This is not an exhaustive list of the astronomical benefits of accurate planetary positions, but it gives a flavor of the value of such positional knowledge and prediction.

1.2. Dependencies

Theory, observation, and application are interdependent, as illustrated in Figure 1. Observations can be interpreted only in the context of our understanding — represented by theoretical models — of the solar system and its dynamics. The observations can then be used to correct and update our theoretical models. The fusion of the two results in planetary (and satellite) ephemerides as well as a better solar system reference frame. The combination of planetary system model — as determined by

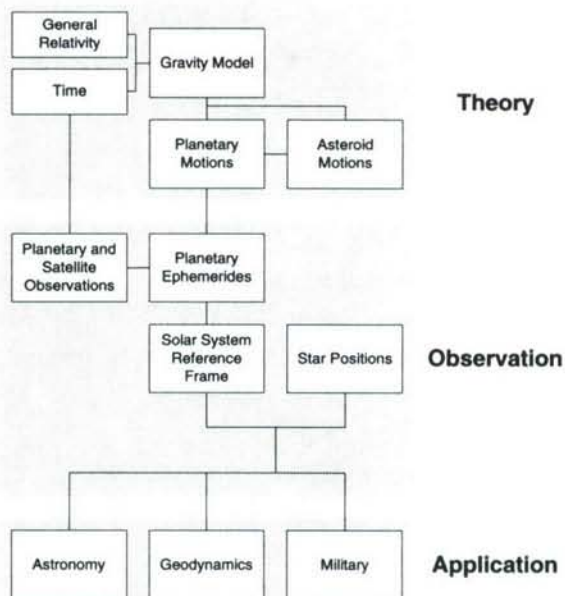


Figure 1 — Interplay between theory, observation, and application.

theory and refined by observations — plus stellar position catalogs, gives rise to a multitude of practical applications in many areas, including astronomy, geophysics, and military.

1.3. Reference Frames

Although we here on the Earth's surface might often prefer to work with a nearly inertial frame of reference tied to the distant stars, we must instead put up with the various noninertial reference frames to which we find ourselves affixed. Defining and/or connecting them is both observationally and theoretically a complex undertaking. We

must tie together a local reference frame, attached to a specific location (and a specific time) on the Earth's surface, to a reference frame that takes into account the spinning and wobbling motions of the Earth. This spinning and wobbling frame can be connected via lunar laser ranging to a frame that encompasses the dynamic solar system, with all its complicated planetary and satellite motions, each body affecting to various degrees the motions of every other body in accordance with Newton's and Einstein's theories of motion in gravitational fields. We then try to join the solar system dynamical frame to a Galactic frame, which takes the form of standard catalog frames such as FK5² or HIPPARCOS³, which are stellar catalogs, or the new ICRF⁴, based on extragalactic objects. The Naval Observatory has been and continues to be among the world's foremost contributors to and creators of these kinds of fundamental position catalogs. Figure 2 is an illustration showing various reference frames, from the largest scale to the smallest, and the kinds of processes or observational methods

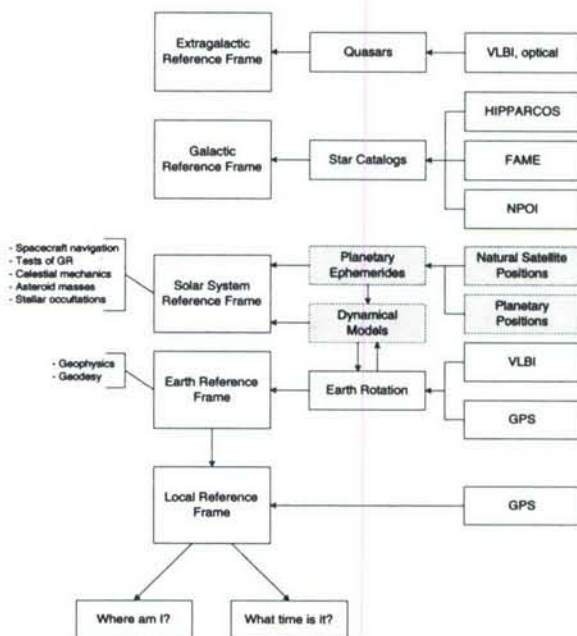


Figure 2 — A reference frame hierarchy, showing the context in which modeling planetary motions (shaded boxes) resides.

that they rely on. The first column is a hierarchy of frames, from the size scale of the universe down to the local and very practical question of “Where am I right now?”. We must attach the notion of time to that of position, since in any dynamical frame the two are inextricably linked. The second column con-

tains the major input category or dynamics type that corresponds to the associated reference frame. The third column lists the most important observation types that determine the reference frame. The activities associated with planetary ephemeris generation correspond to the shaded boxes, and these are the areas we will concentrate on here. Figure 3 shows these same reference frames, but organized to show how they are related to each other observationally.

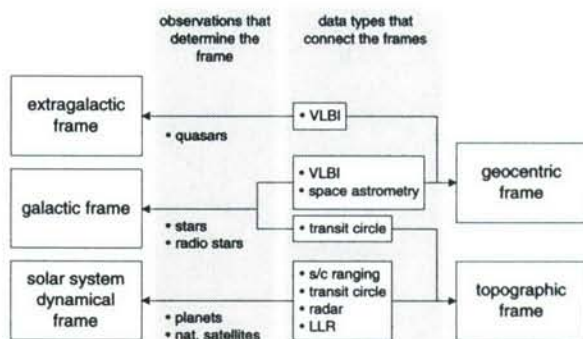


Figure 3 — Connections between reference frames.

1.4. Generating Precise Predictions of Planetary Positions

We have established the need for accurate planetary positions. Therefore, we need to be able to *generate accurate predictions* of planetary positions. These tabulated predictions we call *ephemerides*.⁵ How does one generate an ephemeris? This is a three-stage process, as illustrated in Figure 4.

First and foremost, we must obtain accurate observations. Historically, observations consisted mainly of ground-based optical positions of planets and their satellites. Satellite positions are the more valuable since satellites generally have no atmospheres (and hence no limb-darkening) to contend with. Since they orbit their parent planets in a manner predictable by Newton's law of gravity, their positions can form the basis for determining the parent planet positions. This is complicated considerably, however, by the difficulty in constructing highly accurate theories of satellite motions, caused by the complex interactions of the satellites with each other, with the planets, and with the nonspherical parent planet whose mass distribution we don't always know as well as we'd like. The modern era has seen

the advent of other types of observations, including ground-based radar, lunar laser ranging, spacecraft telemetry, and space-based astrometry. The European HIPPARCOS mission⁶ is a successful example of a space astrometry mission. We hope other missions, such as FAME (USNO)⁷, and SIM (JPL)⁸ or GAIA (ESA)⁹, will follow.

The second step in generating an ephemeris is to develop a comprehensive solar system model that we then integrate numerically. We must include complications, such as planetary (especially Earth) rotation dynamics and lunar motion, as well as more subtle effects, including general relativity, tidal interactions between Earth and Moon, and planetary topography models (for better resolution of radar data). The state of the art has advanced to the point that it is becoming necessary to include the masses of individual asteroids¹⁰ as well as a mass model for the asteroid belt. Both of these kinds of masses are in general very poorly known, yet asteroidal mass uncertainties are now the largest source of error in high-precision ephemerides of the inner planets. Currently, the JPL ephemerides (specifically, DE405) include mass estimates for 300 asteroids. These masses are based on IRAS magnitudes, albedo estimates, and mean density estimates.

The solar system model contains many adjustable parameters, such as masses, orbital elements, initial positions and velocities, gravity model parameters, and so on. The third step in generating an ephemeris is to simultaneously fit all of these model parameters to the available observations. This requires performing a nonlinear least squares analysis of a comparison between a numerical integration of the solar system model and the observational data. This analysis results in (hopefully minor) adjustments to

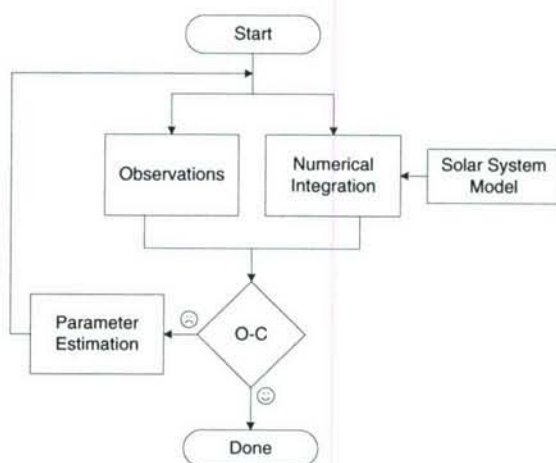


Figure 4 — Generating a planetary ephemeris. Numerical integrations of a solar system model are compared with observational data, resulting in O-C residuals. Based on these residuals, model parameters are refined and the entire process repeated until convergence.

the model parameters. We then integrate the model again, using the adjusted parameter values, then compare again to the observations. We iterate this process until the parameters stop changing appreciably. At that point, we have the best fit of the solar system model to the available observations.

1.5. Observation Types

For observing planetary positions, the various observational data types fall naturally into the two broad categories: timing (in a sense, the radial coordinate from the observer) and positions on the sky (i.e., transverse to the radial direction). The hierarchy of types is illustrated in Figure 5.

1.6. Example: Space-Based Asteroid and Natural Satellite Observations

Figure 6 shows space-based astrometric observations by HIPPARCOS of the 48 asteroids and 3 natural satellites it was able to reach. For the brightest asteroids, the

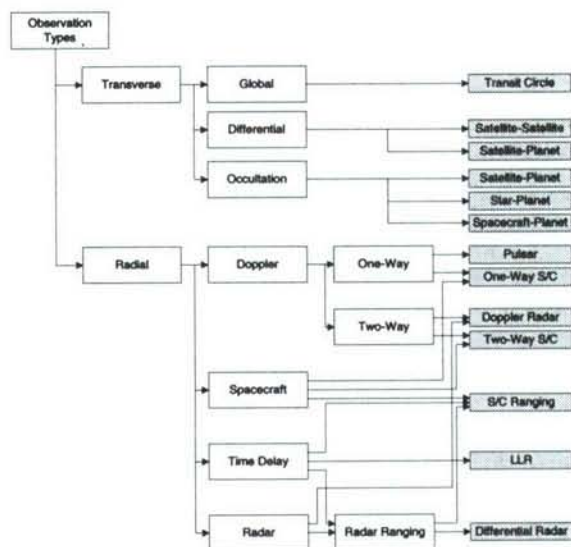


Figure 5 — Observation types.

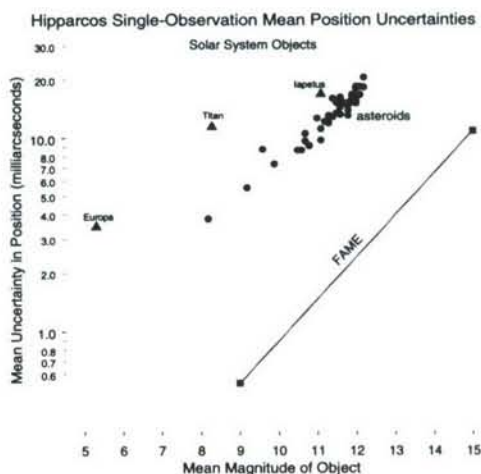


Figure 6 — HIPPARCOS single-observation accuracy of solar system objects, with a comparison to projected FAME single-observation accuracy.

single-measurement accuracy is less than 10 milliarcseconds. The accuracy of the satellites is degraded by the fact that at the resolution of the HIPPARCOS telescope these objects are not point sources but extended bodies, introducing centroiding difficulties. This figure also shows the projected single-measurement accuracy of the FAME satellite¹¹. (The USNO is hoping to launch FAME in 2003 or 2004 as a NASA MIDEX mission.) FAME will be able to do an order of magnitude better than HIPPARCOS in positional measurements of solar system objects. FAME will also go substantially fainter, allowing observations of many more asteroids and natural satellites than HIPPARCOS. Natural satellite observations — especially in the outer solar system — are important because, combined with integrations of their motion, they can be used to obtain the positions of the parent planets much more accurately than observations of the planets themselves. FAME will potentially be able to reach over 20 natural satellites and upwards of 2100 asteroids.

2. NEWCOMB: A SOLAR SYSTEM EPHEMERIS PROGRAM

Newcomb¹² is a new Solar System Ephemeris program currently under development at the U.S. Naval Observatory. In terms of use at the USNO, Newcomb will be the successor of PEP, the Planetary Ephemeris Program maintained at the Smithsonian Astrophysical Observatory¹³, and of the DE series of programs from the Jet Propulsion Laboratory. DE and PEP are the only currently existing high-precision solar system ephemeris programs.

2.1. *Motivation: Why a New Program?*

The developmental origins of both PEP and the DE programs dates from the early to mid 1960s. Both computer program design and language capabilities, as well as the precision of both observational data and the practical needs for that data, have advanced far beyond the anticipations of three and a half decades ago when PEP and the JPL DE programs were originally developed. Program technology that is several generations out of date, combined with the practical inability to add further significant capabilities or modifications to PEP, has been deemed sufficient cause for development of a new ephemeris program. Additional motivations are that it is to the USNO's great advantage to have a comprehensive ephemeris capability in-house (especially since the NAO publishes the *Astro-*

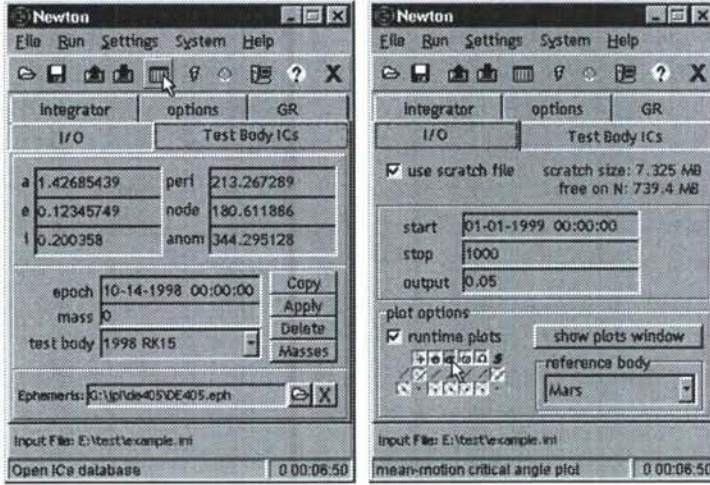


Figure 7 — Examples of a graphical user interface (from Newton)

nomical Almanac), and that Newcomb will provide a check against PEP and the JPL DE programs.

Finally, the creation of a modern ephemeris program provides an opportunity to simultaneously develop a flexible research

tool for investigation of solar system dynamics. The integration module of Newcomb is in large part already completed and exists as a standalone program called Newton.¹⁴ This program is currently being used in the Astronomical Applications Department¹⁵ for investigations of the dynamics of inner solar system asteroids, the asteroidal “noise” in the motions of Earth and Mars, and the dynamics of trans-Neptunian objects.

To highlight the difference between “old” and “new” programming, consider the task of setting program input parameters. Appendix A contains a typical input file used by PEP. Figure 7 shows how it is done using a GUI. The intuitiveness of the GUI approach leads to substantial time savings in coming up to speed in program usage, as well as actual use of the program day to day. Even more valuable is that it allows a much more sophisticated interface and a much more sophisticated set of program capabilities.

2.2. Advantages of Modern Programming and Design

Chief among the advantages of writing a new program is the opportunity to make use of both modern programming and modern design technologies, namely object-oriented programming (OOP) and object-oriented design (OOD), as well as graphical user interfaces (GUIs). Recently, the highly productive “components” programming associated with rapid application development (RAD) environments has greatly enhanced

the efficiency, sophistication, and dependability of GUI programming. Additionally, modern integrated development environments (IDEs) have matured into a powerful and reliable means of rapidly developing, testing, and debugging complex and sophisticated programs. None of these powerful technologies was available until the 1990s. Hence, design and construction of modern programs is faster, safer, and more intuitive. Also very important is the fact that all of the numerical algorithms used in a high-precision ephemeris program — e.g., numerical integrators, nonlinear estimation, etc. — are now mature technologies, which was certainly not the case thirty-five years ago.

Consequently, the Newcomb computational back end is written entirely in ANSI C++, and development and testing are done entirely within the best C++ RAD environment currently available.¹⁶ Throughout the program, we take full advantage of standard OOP/OOD concepts and techniques, including full data encapsulation, template and nested template classes, polymorphism, and, where necessary, multiple inheritance.

The benefits of a completely object-oriented approach are many, including faster prototyping and development, fewer and more easily locatable coding errors, vastly simpler and more intuitive design, more sophisticated functionality, easily extensible architecture, and (most importantly) drastically reduced long-term maintenance costs. Another major benefit is that the program can be brought up and running with minimal functionality, allowing further capability to be easily and relatively painlessly incorporated as need arises.

Ease of extensibility is largely a result of object-oriented design, but it is also directly related to how good that design is. Hence, considerable effort has gone and is still going into the design of Newcomb. Experience in the software industry over the last one to two decades abundantly shows that the payoff later on in terms of maintenance and extensibility is far out of proportion to the effort expended early on — in the design stages — of the program life cycle.

The benefits of a RAD environment for development and testing are also very attractive. Chief among the attractions is the ease by which it is possible to create highly sophisticated graphical user interfaces. During design, graphical interface components — such as buttons, edit fields, toolbars and so on — are “dropped” onto a window form or dialog box. Useful properties of the components are settable at design time, in addition to being available during runtime. It is easy to create custom components as

well. For example, for Newcomb we designed a custom component that is in fact a fully functional and self-contained power spectral density (PSD) analysis package, including plots and file output. All that is needed to add a PSD module to a program is to drop the PSD component onto a form or dialog. Hence, building, changing, and extending the graphical user interface of a program is astoundingly easy once a good overall design has been created. This of course spills over and makes changing or extending major program structural elements correspondingly painless.

2.3. *Newcomb Project Outline*

In these beginning stages of the Newcomb project, tasks naturally fall into three main categories: program design, documentation, and science applications. A rough outline of the most obvious subjects that must be addressed is:

- I. Design Issues
 - A. numerical integration scheme
 1. object-oriented design
 2. Integrable objects have knowledge of dynamical environment as well as the ability to dynamically evolve in that environment.
 - B. exception handling
 1. all exceptions fully recoverable
 2. procedure stack traceback
 - C. robust parameter estimation
 1. Singular Value Decomposition (SVD)
 2. use a mature package from elsewhere
 - D. graphical user interface
 - E. reduction of observations
 - F. individual class design and testing
- II. Science Issues and Projects to Consider
 - A. asteroids
 1. masses from orbital interactions
 2. provide ephemerides (services to the community)
 3. cumulative effects on planetary motions
 - a. Asteroids are the largest source of "noise" in the orbits of Mars and the Earth-Moon system.
 - B. lunar motion
 1. chaotic dynamics
 - a. predictions from numerical models
 - b. comparisons with LLR data
 2. radiation pressure
 3. resonant interaction between tidal and GR terms
 4. lunar librations
 - C. Nordtvedt h parameter (anomalous gravitational field energy effects — i.e., a difference between gravitational and inertial mass proportional to the gravitational binding energy of a body)
 - D. GR precession

1. lunar orbit
2. Earth's spin
- E. bounds on time variation of the gravitational constant
- F. millisecond pulsars
 1. derive Earth orbit
- G. bounds on dark matter in the solar system?
- H. planetary satellites?
 1. centroiding vs. satellite-derived center of mass
- I. other science?

III. Documentation

- A. code
 1. source documentation
 2. interface (user manual)
- B. algorithms
- C. physics
 1. GR and partial derivatives
 2. Earth-Moon tidal interactions
- D. parameter estimation and error and correlation analysis
- E. numerical integration design
- F. reduction of observations

2.4. An Overview of the Newcomb Program Structure

The top level process structure of Newcomb is shown in Figure 8. Basic operation is as follows.

The observations module is responsible for reading input astrometric observations and reducing ("massaging") them as necessary. The observations will be of various types (Figure 5), taken at various observing locations (Figure 11), including spacecraft. The reduction process corrects for various instrumental and other effects (e.g. from the atmosphere) that are specific to a particular set of observations.

The integration module is responsible for numerically integrating a sophisticated dynamical model of the solar system — including general relativistic terms, a detailed Earth-Moon system, planetary spin vectors including preces-

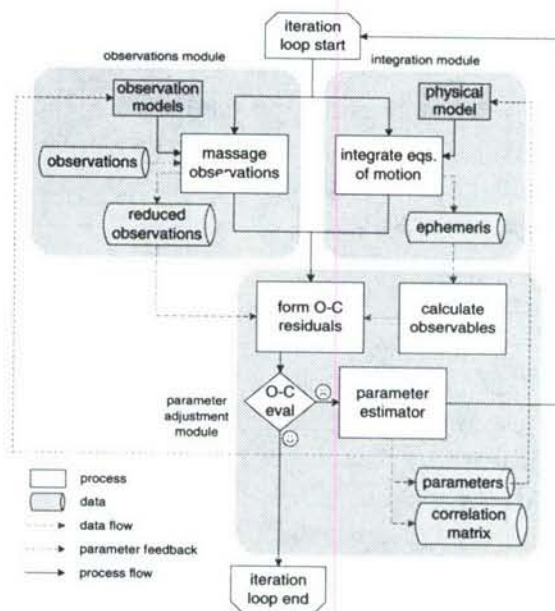


Figure 8 — Major program processes.

sion and nutation, and an unlimited number of asteroids — to produce an ephemeris.

The model ephemeris is then compared with the observations in the O-C section of the parameter adjustment module to produce a set of residuals. The parameter estimator uses the partial derivatives of the model equations with respect to the model parameters (including initial conditions) to solve the associated nonlinear least squares problem for the most probable set of model parameter values that minimizes the O-C residuals.

The adjusted model parameters are then fed back into both the ephemeris generator and the observation transformation methods. The data are rereduced as necessary, and a new ephemeris is generated by the integration module, using the updated parameter values. These are again combined to produce a new set of residuals. This process is iterated until the parameters satisfy predetermined success criteria.

At the end of the iterative process, we will have produced an ephemeris that best fits the observations, given the model used, as well as the best-fit model parameters, formal error estimates of those parameters, and the parameter cross correlations. The parameter error estimates and parameter correlations are derived from the partial derivatives and the correlation matrix from the least squares analysis. Experience with PEP has shown that, normally, at most only a couple or a few iterations are needed

2.5. The Integration Module

The integration module of Newcomb is relatively straightforward, as shown in Figure 9. After choosing which bodies to integrate, one sets all the initial conditions for all the integrated bodies, as well as both the physical model parameters (G, masses, etc.) and the integrator parameters (accuracy limits,

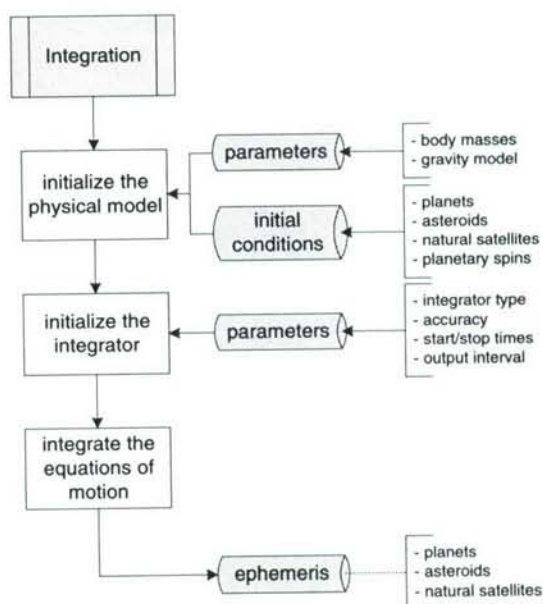


Figure 9 — The Integration Module.

step size limits, etc.). The integrator then integrates the equations of motion, providing intermediate output along the way. The intermediate output varies in complexity, from simple diagnostics to runtime graphics of orbital elements, close approaches, mean-motion resonance angles, and so on. As previously mentioned, the integration module is such an intrinsically useful tool that it has been broken out as a standalone solar system dynamics application, called Newton.

2.6. The Parameter Adjustment Module

The parameter adjustment module is relatively straightforward. The processed observations from the Observations Module and the calculated ephemeris data from the Integration Module are compared, thus forming the O-C residuals. First, coordinate frame compatibility between the observations and the synthetic ephemeris is reconciled. The calculated ephemeris must be transformed to apparent positions in order to match the observations. The residuals are characterized, with statistical and descriptive output going to disk as well as to an output window on-screen. At this point, outlying data points can be automatically — or manually — detected and removed.

The core of the module follows with the determination of parameters via a nonlinear

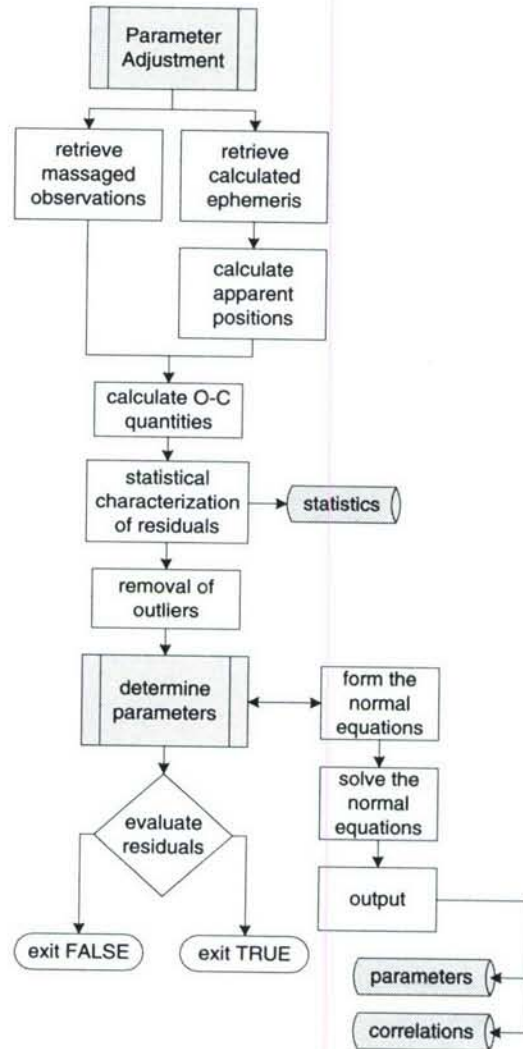


Figure 10 — The Parameter Adjustment Module.

maximum likelihood estimator (e.g., Levenberg-Marquardt). The normal equations are formed and solved, and the parameters and associated formal error estimates are saved. Finally, the residuals are evaluated, and the module exits with a solution “acceptability” code. Figure 10 illustrates the process.

Matrix inversion is accomplished via singular value decomposition (SVD), which is very robust and offers useful diagnostics for ill-conditioned matrices. Singularities are automatically detected and corrected, and the problem parameters are identified. In essence, if the algorithm encounters an ill-conditioned matrix, it safely steps around the problem point(s) and proceeds in such a way as to mine the matrix for the maximum amount of information. When a singularity (rare in practice) or degenerate column (not rare!) is encountered, the combination of parameters that led to the fault is easily extracted. Thus, not only are singularities safely handled, but — more importantly — parameter combinations to which the data are insensitive are automatically identified.

It is unusual to encounter a computational method that is this reliable and blowup-proof. I have already developed and tested matrix inversion using SVD and incorporated it into the Matrix utility class. With regard to Newcomb, SVD is a “plug’n’play” capability.

2.7. The Observations Module

Perhaps the most difficult section of the program is the module that processes input observations and reduces them to a form suitable for passage to the O-C section of the parameter adjustment module (see Figure 10). In essence, the observations are sent to the O-C section in the form of apparent positions, corrected for various biases, including (but not limited to):

- ▶ catalog corrections
- ▶ delay/doppler bias corrections
- ▶ coordinate frame fiducialization
- ▶ aberration corrections
- ▶ nutation and precession

Integral to this section are the specific types of observational datasets and the specific types of observational platforms. The data and platform types vary widely.

2.7.1. Observing Platforms

One must consider the various observing platforms presently available in the solar system. They are

- I. Planet
 - A. Earth
 1. Earth-based observatories
 2. Earth orbiters
 - B. Planetary landers
 - C. Planetary orbiters
- II. Deep space probes (i.e., gravitationally unbound from all planets and satellites)

Figure 11 shows the object hierarchy of observing platforms.¹⁷ The C++ code classes reflect this hierarchy. Each input data stream will contain relevant observing platform information. An appropriate observing platform object will encapsulate this information. Each type of platform object also encapsulates the necessary functionality (referred to as *methods*) to provide information needed to manipulate or transform data of the corresponding type (see Figures 5 and 11).

For example, planetary observing platform objects know how to precess and nutate coordinates to a specified epoch. Each base class contains parameters and functionality common to all subclasses derived from it. The derived classes contain only the additional or specialized parameters and functionality required to handle platforms of a specific kind. For example, since all planetary platforms have a basic precession and nutation capability, these methods reside in the base class PlanetPlatform. An EarthPlatform object automatically inherits all the functionality and data of PlanetPlatform. The EarthPlatform object therefore contains only additional abilities, data, or refinements, for ex-

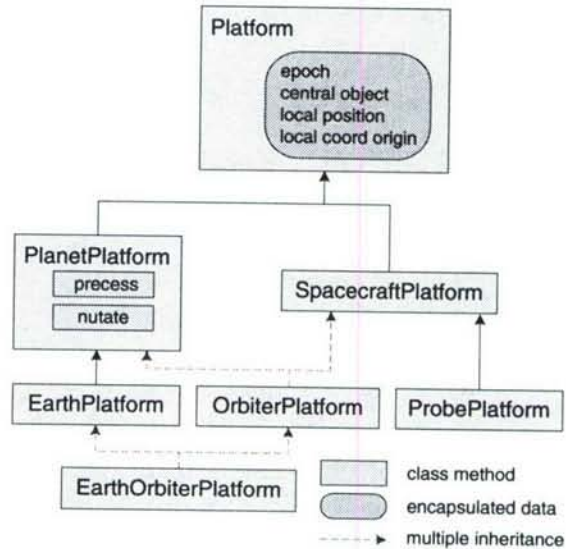


Figure 11 — Observing platform class hierarchy.

ample precession parameters specific to the Earth. Proper use of inheritance eliminates code duplication for common tasks in a natural and intuitive way. The inheritance mechanism is built into the C++ language and therefore requires no enforcement by or special discipline from the programmer.

Figure 11 intentionally shows only the major class types, in accord with the introductory nature appropriate to this Chapter. It is a simple matter to derive further specialized classes from the base classes shown. For example, one would derive a *VikingOrbiter* from *OrbiterPlatform*.

2.7.2. *Observation Types*

As previously mentioned, the various observation data types fall naturally into the two broad categories: timing and position. For reasons having mainly to do with datasets that are currently insufficiently large or insufficiently accurate to have a substantial effect on ephemeris accuracy, early versions of Newcomb will not include some of the observation types. Newcomb will include the following subset types:

- | | |
|---------------------------|----------------------------|
| I. Transverse (position) | b. Spacecraft |
| A. Optical observations | 2. Twoway |
| 1. Global positions | a. Radar |
| a. Transit circle | b. Spacecraft |
| 2. Differential positions | B. Time delay observations |
| II. Radial (timing) | 1. LLR |
| A. Doppler observations | 2. Radar |
| 1. Oneway | a. Differential radar |
| a. Pulsars | 3. Spacecraft |
| | a. Single |

Because extensibility is built into the design of Newcomb, adding further capabilities as they become necessary will involve minimal effort — there is no need, from a maintenance standpoint, to include capabilities that are anticipated to go unused for a long time. That is, with a good object-oriented design we do not have to worry so much about “making room” for anticipated future capabilities. Figure 5 shows the observation types hierarchy. Figure 12 shows the proposed corresponding object class hierarchy used in Newcomb.

Each type of input data stream will contain embedded type information, and instantiations of the appropriate data objects will handle the data. The

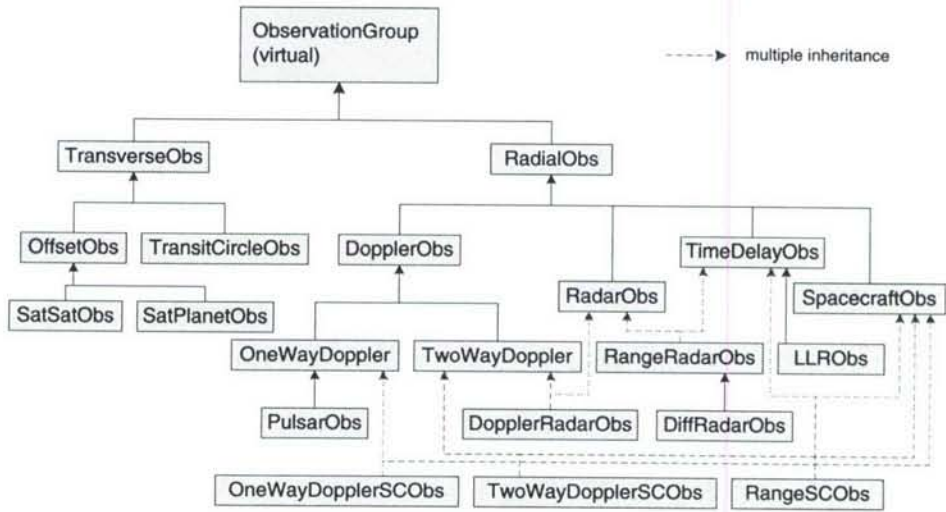


Figure 12 — Observational class hierarchy.

specific objects shown in Figure 12 encapsulate not only the corresponding observational data but also the functionality required to reduce that data type. For example, notice that all datatype objects have, via inheritance from the base class *Observation*, platform information and the ability to handle (say) aberration.

As with Figure 11, Figure 12 is intentionally not complete, especially regarding encapsulated data and method details. However, all the important base classes, and their inheritance dependencies, are shown.

3. SUMMARY

We have given a brief description of the field of high-precision modeling of solar system planetary and natural satellite motions. Motivations for high-precision ephemerides stem from — perhaps surprisingly to many — military as well as astronomical requirements. The latter category includes such areas as spacecraft navigation, celestial mechanics, occultation predictions, tests of General Relativity, etc. Several kinds of observations go into determining high-precision ephemerides — essentially, we use anything we can get our hands on. We have also discussed in broad terms the method of generating high-precision ephemerides, making use of both observational data sets and comprehensive models to solve for the “best” model parameter values.

Given that the extant first generation of high-precision ephemeris programs is antiquated, the U.S. Naval Observatory has begun development of a new, highly flexible ephemeris program called Newton. This modern program takes full advantage of design and programming techniques developed in the 1980s and early 1990s and now available as a mature set of technologies. An overview of the program design has been presented, which serves also to provide further insight into how a modern, high-precision solar system ephemeris can be generated, as well an indication as to some of the complexity of such an undertaking. It is relatively simple and straightforward to write a program that makes low-precision predictions. However, generation of a high-precision ephemeris is another matter altogether.

APPENDIX: TYPICAL PEP INPUT

As an example of the old-style program interface, following is a small excerpt taken from a typical PEP input file. Compare to Figure 7. This particular file (courtesy James Hilton) was used in the generation of ephemerides for the four largest asteroids for use in the Astronomical Almanac for the year 2000.

```
Ephemerides improvement for the first 4 asteroids.
&NMGST1
EXTPRC= 0,          $ Use hardware extended precision
ICT(1)= 10,
ICT(3)= 1,
ICT(4)= 1,          $ Compute partial derivatives
ICT(5)= -1,         $ Do not use saved normal equations
ICT(9)= 0,
ICT(10)= -2, ICT(11)= -2,
ICT(12)= 2,         $ prediction or harmonic analysis
ICT(34)= 3,
ICT(39)= 1,
ICT(50)= 1,         $ USE BROWN MEAN MOON IF NO IPERT
ICT(80)= 0,
JCT(13)= 1,         $ Use J2000.0 coordinates.
JCT(33)= -1,        $ Use USNO UT1 and wobble
JCT(27)= 1,         $ Use * commands
JCT(28)= 7,
MASS(1)= 6023600.D0, $ Use DE200 masses for the planets
MASS(2)= 408523.D0,
MASS(3)= 328900.55000000000047D0,
MASS(4)= 3098710.D0,
MASS(5)= 1047.35001090551827D0,
MASS(6)= 1497.999999841770460D0,
MASS(7)= 22960.0000007059389D0,
MASS(8)= 19314.0002382557432D0,
MASS(9)= 130000000.238686755D0,
MASS(10)= 0.012150581D0,
MASS(11)= 2.239D9,
MASS(12)= 9.247D9,
MASS(13)= 8.7D10,
MASS(14)= 7.253D9,
MASS(17)= 1.849D11,
AULTSC= 499.0047837D0, $ AU in light seconds
ECINC= 23.439281083D0, $ Use Del18 Obliquity
PRMTR(47)= 0.0D0,      $ RA OF ASC, NODE OF BELT
PRMTR(48)= 23.4433D0,  $ INCLINATION OF BELT
PRMTR(49)= 2.9D0,      $ DISTANCE OF BELT FROM SUN
PRMTR(50)= 8.7372530294101D-10, $ MASS OF BELT
PRMTR(81)= 0.0D0,
MDSTSC= 0.,           $ MOON TAPE DISTANCE UNIT IN AU
NBODY= 0, IPERT= 10,
NUMBT= 1,
IOBS= 30,
IOBS1= 14, IOBS2= 15,
$ EPS(3)= 100,
$ EPS(4)= 100,
LPRM(1)= 11, LPRM(2)= 12, LPRM(3)= 14,
*OBJECT EARTH-ROTATION
CON(22)= 5029.0966,
CON(23)= 84381.4119,
*OBJECT 11
NAME= ' CERES ',
INCND= 0, ITAPE= 31, NCENTR= 0, JTYPE=6,
A= 2.767121817D0, E= 0.07749262D0, INC= 27.116375D0,
ASC= 23.471566D0, PER= 133.40890D0, ANOM= 2.08129D0,
JDI= 2378801, JD2= 2450001, JDO= 2444801,
K(31)= 1, K(32)= 1, K(33)= 1, K(34)= 1, K(35)= 1, K(36)= 1, K(37)= 1,
K(38)= 1, K(39)= 1, K(40)= 1, K(41)= 1, K(42)= 1,
K(43)= 1, K(44)= 1,
K(61)= 1,          $ Include GR
K(87)= 2, INT= 2,   $ INTERVALS
K(88)= 2, K(89)= 6, $ ADAMS-MOULTON, 7 TERMS
K(91)= -3, K(92)= -6, EPS(3)= 1E-9 $ STARTING INTERVALS
K(98)= -500, K(99)= 0, K(100)= -1, $ PRINT = TAPE, ORDINARY EQNS OF MOTION
KI= 1, 1, 1, 1, 1, 1, 1, 1, 12, 13, 14,
L= 1, 1, 1, 1, 1, 1,
*OBJECT 12
NAME= ' PALLAS ',
INCND= 0, ITAPE= 32, NCENTR= 0, JTYPE=6,
A= 2.771672932D0, E= 0.23396027D0, INC= 11.809637D0,
ASC= 161.02570D0, PER= 322.7875D0, ANOM= 298.543057D0,
JDI= 2379251, JD2= 2450001, JDO= 2449601,
K(31)= 1, K(32)= 1, K(33)= 1, K(34)= 1, K(35)= 1,
K(36)= 1, K(37)= 1,
K(38)= 1, K(39)= 1, K(40)= 1, K(41)= 1, K(42)= 1,
K(43)= 1, K(44)= 1,
K(61)= 1,          $ Include GR
K(87)= 2, INT= 2,   $ INTERVALS
K(88)= 2, K(89)= 6, $ ADAMS-MOULTON, 7 TERMS
K(91)= -3, K(92)= -6, EPS(3)= 1E-9 $ STARTING INTERVALS
K(98)= -500, K(99)= 0, K(100)= -1, $ PRINT = TAPE, ORDINARY EQNS OF MOTION
KI= 1, 1, 1, 1, 1, 1, 1, 1, 11,
L= 1, 1, 1, 1, 1, 1,
*OBJECT 13
NAME= ' JUNO ',
INCND= 0, ITAPE= 33, NCENTR= 0, JTYPE= 6,
A= 2.670660949D0, E= .25626106D0, ANOM= 156.782239D0,
INC= 10.814499D0, PER= 46.75209D0, ASC= 11.27760D0,
JDI= 2380151, JD2= 2450001, JDO= 2444801,
K(31)= 1, K(32)= 1, K(33)= 1, K(34)= 1, K(35)= 1, K(36)= 1,
K(37)= 1,
K(38)= 1, K(39)= 1, K(40)= 1, K(41)= 1, K(42)= 1, K(43)= 1,
K(44)= 1,
K(61)= -1,
```

- 1 One arc second is equal to one 3600th of a degree. One milliarcsecond equals one one-thousandth of an arc second. To provide some context, consider that 1 arcsecond corresponds to 1/16 of an inch around the perimeter of the 1000-foot radius Observatory Circle here at USNO. How much is 50 *microarcseconds* [the nominal accuracy of the proposed space astrometry mission FAME (<http://aa.usno.navy.mil/FAME/>)]? That is the angle subtended by the width of a typical strand of human hair as seen from a distance of 65 miles.
 - 2 <http://adc.gsfc.nasa.gov/adc-cgi/cat.pl?/catalogs/1/1149A/>
 - 3 <http://astro.estec.esa.nl/Hipparcos/hipparcos.html>
 - 4 For an informative introduction to the International Celestial Reference System (ICRS), see http://aa.usno.navy.mil/AA/faq/docs/ICRS_doc.html. The ICRF catalog and related information is available at <http://hpiers.obspm.fr/webiers/results/icrf/README.html>.
 - 5 From the Greek *ephemeros*, meaning *daily*. That is, a table of coordinates of a celestial body at specific times.
 - 6 <http://astro.estec.esa.nl/Hipparcos/hipparcos.html>
 - 7 <http://aa.usno.navy.mil/FAME/>
 - 8 <http://sim.jpl.nasa.gov/>
 - 9 <http://astro.estec.esa.nl/SA-general/Projects/GAIA/gaia.html>
 - 10 James Hilton of USNO is the world's foremost expert in determination of asteroid masses. See http://aa.usno.navy.mil/hilton/asteroid_masses.htm
 - 11 See the FAME homepage at <http://aa.usno.navy.mil/FAME/>
 - 12 See the official Newcomb program web site at <http://aa.usno.navy.mil/Newcomb/>. As reviewed elsewhere in these Proceedings, Simon Newcomb (1835-1909) was a remarkable force in 19th century American mathematics and astronomy. He was Superintendent of the Nautical Almanac Office from 1877 to 1897, and he devoted much of his prolific career to (in his words)

...a systematic determination of the constants of astronomy from the best existing data, a reinvestigation of the theories of the celestial motions, and the preparation of tables, formulae, and precepts for the construction of ephemerides, and for other applications of the same results.
- See also the biography page located at <http://www-history.mcs.st-and.ac.uk/~history/Mathematicians/Newcomb.html>
- 13 See <http://cfa-www.harvard.edu/~reasen/ssd.html> for information about PEP.
 - 14 <http://aa.usno.navy.mil/Newton/>
 - 15 <http://aa.usno.navy.mil/AA/>
 - 16 <http://www.borland.com/bcppbuilder/>
 - 17 Arrows in Figures 11 and 12 point *from* derived classes *to* parent (also called *base*) classes. This is the standard notation.

THE FUTURE OF ALMANAC DATA IN THE UNITED KINGDOM

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Introduction

It is well over two hundred years since the first British Nautical Almanac appeared, and almost 170 years since a dedicated Nautical Almanac Office was established in England. With such a record of longevity, it might be thought that almanac data in the United Kingdom had an assured future, and on statistical grounds alone imminent demise would not be expected. Unfortunately these conclusions are by no means safe—the adverse pressures that almanac offices everywhere experience have never been stronger. In fact, it is not too much of an exaggeration to say that the principal activity of Her Majesty's Nautical Almanac Office over the last decade has been the struggle for survival.

The main difficulty, paradoxically, is that a nautical almanac office has many roles and a large and varied customer base. While an almanac for mariners is a clear deliverable, serving a well-defined community, producing it is rarely the activity that dominates the workload or provides the primary intellectual stimulus for the staff.

The fact is that an almanac office is simply expected to *be there*, ready to predict the phases of the Moon and times of sunrise and sunset, to rule on whether the Sun was in a position to dazzle a driver, and to say how long before dawn a military target will be visible. But defence agencies may be reluctant to fund activities they see as mainly civilian, and no one government department is likely to accept that it should be responsible for supplying all types of almanac information to anyone who requests it. Furthermore, the staff who know how to do these things—from first principles, without having to ask anyone else, and always getting the right answer—are, in many cases, engaged in dynamical and positional astronomy research. Unfortunately, for many decades now, astronomy has been the poor relation to astrophysics when it comes to bidding for research grants.

In recent years, these pressures have been compounded by rapidly changing technology. Personal computers are now perfectly capable of

calculating everything in the Almanac—with the right software. Many individuals and companies can predict Sun, Moon and planet positions. The public expects everything to be free, on the Web. And GPS has swept all before it to become the primary method of navigation at sea (though not always to be relied upon, as we have already heard¹).

This paper falls into three main sections: the history of Her Majesty's Nautical Almanac Office up to the closure of the Royal Greenwich Observatory in October 1998, the move of the Office to the Rutherford Appleton Laboratory at that time, and the future. Given what has been said already, it should come as no surprise that the paper concentrates more on funding than on science, and reaches few, if any, clear conclusions about what will happen next.

History

A detailed history of HMNAO has already been provided in these *Proceedings*², but I will present a summary, to set the scene.

The Nautical Almanac and Astronomical Ephemeris was published for the first time in 1767, but it was not until 1831 that the Nautical Almanac Office was established.* In 1936, the Admiralty shifted the responsibility for the Nautical Almanac Office from the Hydrographer to the Astronomer Royal, a transition which illustrates the “homeless” status of almanac offices referred to earlier. In 1949, when the Royal Observatory relocated to Herstmonceux and became the Royal Greenwich Observatory, HMNAO, then located in Bath, moved there as well. In 1965, when the Science Research Council took over the RGO from the Admiralty, HMNAO became a department of the RGO.

In 1989, the Particle Physics and Astronomy Research Council (successor to the Science and Engineering Research Council and before that the Science Research Council) signalled that they were no longer prepared to fund HMNAO. The management of RGO, wishing HMNAO to continue, decided that it would henceforth be financed entirely from the income it brought in from publications and services. This change introduced tensions that are still unresolved today. Which activities should

* This was a consequence of the 1828 Act of Parliament (9 Geo 4 c.66) which requires “the Lord Admiral or commissioners of his office to cause such nautical almanacks to be constructed, printed and published.” The “H.M.” made its appearance in 1907, for obscure reasons.

be pursued? Those that the community takes for granted? The HMNAO staff's research interests? Or only those that are profitable? In short, what is the *mission* of a self-funding Nautical Almanac Office?

After moving the RGO to new premises in Cambridge in 1990, PPARC subsequently decided to close the Observatory, and did so in October 1998.

The Move to RAL

The closure of the RGO meant that a new home for HMNAO had to be found, in order to satisfy the various statutory obligations and to supply information for PPARC's outreach programme. Several options were considered, including privatization, but ultimately the decision was made to relocate the Office to the Rutherford Appleton Laboratory. RAL recognized opportunities for synergy between HMNAO's work and some of its existing programmes; it also took the view that the Office had an important role and should continue.

The HMNAO staff transferred to RAL during the final quarter of 1998.

CCLRC and RAL

The Rutherford Appleton Laboratory, HMNAO's new home, is located in Oxfordshire, about 60 miles from London. It is one of three establishments operated on behalf of the Council for the Central Laboratory of the Research Councils. CCLRC, with 1700 staff and an annual turnover of about \$160M (1998 figures) is one of Europe's largest multi-disciplinary research organizations. It is one of several Research Councils, whose Government sponsor is the Department of Trade and Industry; CCLRC receives very little direct funding from government, in fact, and is supported almost entirely from contracts with other Research Councils and with industry.

RAL, by far the largest of CCLRC's establishments, provides high-technology support in a variety of fields. HMNAO is located in RAL's Space Science Department, which alone has 180 staff and an annual turnover in excess of \$25M.

Staffing

There has been a steady decline in HMNAO staff numbers for many years, as is clear from the lists published in *The Astronomical Almanac*.

The 1981 issue, the first in the present format, is a convenient starting point. In 1979, when this issue went to press, fourteen staff were listed; two years later the team was down to twelve, dropping to eleven in 1984, to eight in 1985, seven in 1988, six in 1989 and four in 1990. There are several causes. The introduction of new technology, a process that had been going on for decades, led to some efficiency gains; and certain activities were moved out of HMNAO into specialist groups. But a significant fraction of the reduction was simply due to “downsizing”.

The transfer of HMNAO to RAL in 1998 was carried out under terms and conditions that protected the interests of the existing staff, and so it was possible to offer all four the opportunity to make the move. In the event, three of the four accepted the offer, and they transferred at the end of the year. The team consists of S. A. Bell, C. Y. Hohenkerk and D. B. Taylor. Bell manages the group and reports to the author. Several other RAL staff work with the group in a variety of capacities; special mention should be made of J. C. Sherman, who as the architect of the commercial future of the operation has a crucial role.

HMNAO's Contractual Framework

The major commitments that establish the context for the Office's work are these:

The recognition by CCLRC of the legal obligations concerning the production of *The Nautical Almanac*. The responsibility is, strictly speaking, borne by the Secretary of State for Defence.

A group of contracts with the Particle Physics and Astronomy Research Council, who were previously responsible for HMNAO. These contracts cover the circumstances and costs of the transfer and various indemnity arrangements and other undertakings.

A publishing agreement with The Stationery Office. Formerly “Her Majesty's Stationery Office”, the official government publisher, TSO is now a private company. Most, but not all, of HMNAO's publications are handled by TSO at present.

An agreement with the National Maritime Museum to provide the almanac-related information—tables of sunrise/sunset for instance—used by the public information service (transferred from RGO to NMM after the 1998 closure).

A Memorandum of Understanding with the U.S. Naval Observatory. HMNAO and USNO have collaborated in the preparation, publication and distribution of astronomical data over a long period of time. Initial co-

operation began in 1900 and has continued since then. The details of the collaboration have varied over the years according to organizational changes and the progress of technology. The MoU, which was renegotiated at the beginning of 1999, affirms the desire of the two organizations to be joint authors and publishers of *The Astronomical Almanac* and other publications and to continue the successful collaboration between the two offices.

The Activities of HMNAO

The Office's activities can be grouped under three main headings: publications, information services and techniques. The heart of the operation is the set of publications that HMNAO produces. The current list is as follows:

- The Astronomical Almanac* (with USNO)
- The Nautical Almanac* (with USNO)
- The Star Almanac for Land Surveyors*
- The UK Air Almanac*
- The Air Almanac* (with USNO)
- Compact Data for Navigation and Astronomy*
- Sight Reduction Tables for Air Navigation* (with USDMA)
- 1999 Eclipse (various books, leaflets *etc.*)
- Technical Notes
- Information Sheets

In addition, extracts and specialist data are produced as required.

Although the Office's principal task at present is simply to restore normal service after a very disruptive and time-consuming move, several other activities are planned. In collaboration with the USNO, revisions of *The Astronomical Almanac* are in hand, to bring the publication into line with the ICRS and the latest JPL solar-system ephemerides, to improve the accuracy and layout of the planetary satellite section, and to introduce a variety of other improvements. An updated edition of *Compact Data* is being prepared, along with an improved version of the *NavPac* navigation software. New publications are to be introduced, in order to bring in more income; in addition, the publishing arrangements of existing ones are being reviewed to eliminate known breaches of copyright. There are plans to exploit new techniques, including CD-ROM and the Web. And last, but not least, is HMNAO's involvement in the IAU's Standards Of Fundamental Astronomy initiative.³ The purpose of SOFA is to provide a

collection of definitive astronomical algorithms and standards for use in astronomical computing. Following the move to RAL, HMNAO now provides two members of the SOFA Reviewing Board, namely the author, who chairs the Board, and C. Y. Hohenkerk, who acts as secretary.*

The Future

In an ideal world, an organization like HMNAO would set out by stating its objectives, and then determine what level of resources will be needed to carry them out. However, that is not the position. Instead, the resources have been defined in advance—namely the income from sales of publications. There is a natural imperative to safeguard, and if possible increase, this income, and an obvious measure to take is to abandon those publications that do not pay their way. However, that is not the outlook of the HMNAO staff themselves, and it jars with the traditions of the Office.

So what is HMNAO's mission?

To ensure that reliable almanac data and publications continue to be available.

To provide expertise and authority in almanac-related areas of astronomy.

To contribute to international astronomy collaborations.

The steps that will be taken to enable these activities to flourish are: to increase return on existing publications; to introduce new products (publications, data, software products *etc.*); to secure proper funding for the information provision role; to secure proper funding for the defence and maritime role; and to solicit contract work.

Acknowledgements

I would like to give my thanks to the U.S. Naval Observatory for the opportunity to present this paper, to Catherine Hohenkerk and Steve Bell for their advice during its preparation, and to the whole HMNAO team for their fortitude over recent months.

* The USNO also provides two Board members: D. McCarthy and G. Kaplan. There are currently nine members in all.

NOTES

1. W. J. Brogdon Jr., "Celestial Navigation by U.S. Civilian Mariners near the End of the Second Millennium A.D.," these *Proceedings*.
2. G. A. Wilkins, "A History of the British Nautical Almanac Office," these *Proceedings*.
3. P. T. Wallace, "SOFA: Standards Of Fundamental Astronomy—Progress and Plans," *Highlights of Astronomy* Vol. 11, Kluwer Acad. Publ.

THE FUTURE OF ALMANAC DATA IN THE UNITED STATES

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Introduction

Numerous factors -- such as changes in technology, navigation policy, user requirements, and funding levels -- make it difficult to predict the future of almanac data in the U.S. In the last few years, there have been detailed discussions of the future of almanacs, both within the U.S. Naval Observatory (USNO), and between USNO and the staff of H.M. Nautical Almanac Office (HMNAO) of the UK. Some definite decisions emerged from these discussions. In some cases, the decisions are already being put into practice. In other cases, the decisions are forming the basis of long-term plans for changes in the products produced by the two almanac offices.

This paper will draw on the discussions mentioned above and present current plans for the future of almanac data produced or co-produced by USNO's Astronomical Applications (AA) Department. This paper will use a broad definition of "almanac data," to include not only printed almanacs, but also software almanacs and almanacs designed for use on the Internet. As with any attempt at making predictions, this paper will inevitably reflect the views and biases of the author.

Future of Celestial Navigation

The future of the navigational almanacs is tied to the future of celestial navigation. In certain respects, the general concept of celestial navigation is more important today than it was ten years ago. The great success and widespread use of the Global Positioning System (GPS) have resulted in the termination or proposed termination of older alternative electronic navigation systems. Prudent navigation practice requires both a primary and a secondary means of navigation, with the secondary independent of the primary. Celestial navigation remains one of the few independent alternatives to GPS.

Celestial navigation can encompass any method that utilizes observations of astronomical bodies -- bodies with known positions in a

standard celestial reference frame -- to determine the position of a platform in a standard terrestrial reference frame. The various methods for performing celestial navigation can be grouped into three general categories. *Traditional, manual methods* require use of the sextant, coupled with manual sight planning and reduction procedures (i.e. printed almanacs and forms). *Traditional, computer-based methods* also require use of the sextant, but sight planning and reduction are performed using a computer program. Finally, *fully automated methods* use some type of automatic electronic sextant or star tracker to make observations, which are then fed to software that performs the sight reduction.

The AA Department plans to be involved in all three of these methods. Prospects and proposals for the navigational almanacs -- both printed and computer-based -- will be discussed below. The AA Department is also engaged in a study of a fully automated system for celestial navigation¹, although further discussion of this topic is beyond the scope of this paper.

Almanacs for Marine Navigation

USNO's proposed plan for the future role of *The Nautical Almanac* in the U.S. is based on input from fleet navigators and our own vision of the role of celestial navigation in today's Navy. The goal of the plan is to promote a computer-based system for planning and reducing sextant observations as the preferred method for routine use, while retaining manual methods, including use of printed almanacs, for backup or emergency use.

Computer-based methods of sight planning and reduction have obvious advantages: they are much faster than manual methods, they eliminate math blunders, they can be made rigorous, and they allow the navigator to take more sights and improve skills in use of the sextant. Fleet navigators have made these points when commenting on USNO's own computer-based almanac for celestial navigation, STELLA.

However, some navigators have expressed great concern about over-reliance on computers and electronics, especially during hostilities. As one navigator stated in a 1997 survey of STELLA users: "A PC based system won't do me any good if I have to perform sight reduction after battle damage, or heaven forbid, in a lifeboat." Another navigator stated: "Electronics like this... [are] placing the Navy in serious jeopardy. Electronic warfare and other technology can easily disable these systems.

Until you have addressed all of these issues, any decent [quartermaster] will opt for conventional means."

In my opinion, both the advantages of computer-based tools and concerns involving over-reliance on technology are valid issues that must be addressed in any plan for the future of the navigational almanacs. Thus, we have proposed that the U.S. Navy fully approve and promote STELLA for routine use in celestial navigation. We also propose that a manual means of sight planning and reduction be retained, but relegated to a backup role. If this policy is adopted, USNO will likely produce an "Abridged Nautical Almanac" specifically for Navy use. This book will be published every three to five years (to be determined) without the hourly tabular data for the Moon and planets. Discussions with fleet navigators indicate that the Moon and planets are often avoided, due to additional complexities in reducing their observations. Of course, STELLA handles these complexities automatically, and STELLA has the capability to generate lunar and planetary almanac data in standard *Nautical Almanac* format on demand. HMNAO would continue to produce the current *Nautical Almanac* and ensure its availability in the U.S.

It is important to note that this plan is only a proposal at this time.

Almanacs for Air Navigation

The future of the U.S. *Air Almanac* is uncertain. Without a doubt, use of celestial navigation aboard U.S. military aircraft is in rapid decline. New aircraft, replacing existing aircraft, are being built without sextant ports. GPS and inertial navigation systems are becoming dominant. Reflecting this situation, there has been a major reduction in celestial navigation training for military air navigators. "Undergraduate" training has essentially been eliminated, and "post-graduate" training has been reduced to a computer-based course. Furthermore, we have been unable to identify any specific U.S. Navy or Air Force requirements for continued publication of *The Air Almanac*. The AA Department undertook a survey of users of *The Air Almanac* in 1998. The survey results are still being analyzed, but preliminary results indicate that there currently is a need for the book. Furthermore, it appears that there will be at least several types of military aircraft that will use celestial navigation for the foreseeable future. Additional study is needed to understand the requirements. However, it is quite possible that the U.S. *Air Almanac* will be reduced in scope or terminated within the next five to ten years.

USNO has offered to produce for the U.S. military a version of STELLA specifically designed for air navigation, but so far there has been no formal interest.

The Astronomical Almanac

The Astronomical Almanac has not undergone a major review and revision since the edition for 1984. The recent adoption of the International Celestial Reference System (ICRS)² by the International Astronomical Union (IAU) will require changes in the book, so there is now an excellent opportunity for a complete review of the contents of the volume. In fact, the AA Department and HMNAO have already begun the process. A survey of users of *The Astronomical Almanac* was undertaken in 1998. While the results are still being analyzed, it is clear that there is strong support for continued production of a printed *Astronomical Almanac*. Numerous survey respondents expressed thoughtful suggestions concerning material in the book that could be added, deleted, or revised. The almanac offices have given, and will continue to give, careful consideration to these suggestions in making decisions concerning the future of the volume.

Changes to *The Astronomical Almanac* will take place gradually, with the first revisions likely to be incorporated into the edition for year 2002. Both content and presentation will be affected. IAU standards will be adopted whenever possible. One of the most interesting changes will be the addition of an "electronic component" to the book. This electronic component will likely take the form of Uniform Resource Locators (URLs) placed throughout the book. These URLs will refer the user to World Wide Web (WWW) sites and services that extend the usefulness of the printed reference data. For example, Section A (Phenomena), which contains extensive tables of sunrise and sunset times, may include the URL of a WWW service that computes times of sunrise and sunset for a specific date and location. Section D (Moon) may include the URL of a File Transfer Protocol (FTP) server from which the lunar ephemeris polynomials can be downloaded and subsequently used in a computer application.

In the long term, the fundamental ephemerides produced by the Newcomb project³ are expected to form the basis of *The Astronomical Almanac*.

In addition to changes in content and presentation, both almanac offices are adjusting the production schedule for *The Astronomical Almanac*. Our survey results indicate that most users would like to have the book one year prior to the cover year. This is our goal and we have already made great progress in attaining it.

The AA Department and HMNAO are also considering replacing *Astronomical Phenomena* with an expanded publication aimed at a more general market.

Computer-Based Almanacs

At first thought, it may seem as if computer-based almanacs and printed almanacs are competing products. I am often asked if our computer-based almanacs, MICA⁴ and STELLA, will allow us to stop production of their printed counterparts. I view the computer almanacs and the printed almanacs not as competing products, but as complementary products. There are many instances when it is much more convenient to look up a value in a book, rather than obtain it from a computer program. Books also stand the test of time, transcending changes in technology that can render a computer program useless. On the other hand, computer almanacs can provide information that is difficult to obtain from a printed book. For example, the topocentric coordinates of the Moon are much easier to obtain from a computer program -- they are computed on demand for a specified location and time -- than from a book, where tabulated geocentric values must be interpolated and transformed to the location of interest. Furthermore, the long time span of a computer almanac makes it very useful for planning purposes.

Also, in my opinion, the widespread availability of astronomical data on the Internet does not eliminate the need for or the usefulness of computer almanacs, although this situation could change as technology advances. Computer almanacs are still usable when an Internet connection is not available. Furthermore, a richer set of user interface features is available in a modern personal computer (PC) program than is currently available in an Internet data service. This allows the almanac developer to create easier and more powerful methods for interacting with the user, and more flexible options for presenting the computed data.

Thus, the AA Department plans to continue improving and supporting MICA and STELLA. They will continue to be targeted to operate on PCs, which enjoy widespread use throughout the world. We are

currently engaged in projects to convert the programs from their current MS-DOS underpinnings, to full compliance with the latest Microsoft Windows operating systems. The printed almanacs generally provide high-precision data in tabular form, and our computer almanacs will continue to follow this prescription. No attempts will be made to compete with the numerous planetarium-type programs that are currently available, although graphics may be introduced if deemed appropriate.

The AA Department also produces another type of specialized computer-based almanac that I will call an "almanac engine." An example of this is the Solar-Lunar Almanac Core (SLAC), available only to our U.S. military customers. In recent years, there has been an increasing demand for illumination data, largely to support planning for night operations and for use in simulators. SLAC is a self-contained, integrated set of C-language functions that computes all important quantities related to illumination: times of sunrise, sunset, moonrise, moonset, twilight, and transit, fraction of the Moon illuminated, and an estimate of the illuminance. SLAC is not a stand-alone program -- rather, it was designed for incorporation into larger software systems, such as ones that do operations planning, mission scheduling, or simulations. SLAC has been quite popular and will continue to be supported and improved. The AA Department will also consider developing similar specialized almanac engines to support specific requirements.

Almanac Data on the Internet

The AA Department has already developed a strong presence on the Internet, and that presence will almost certainly increase. We use our Web site for several key tasks. First, we use the site to advertise, and help customers obtain, the printed and computer-based almanacs. Second, we use the site to describe basic astronomical phenomena and to provide answers to frequently asked questions about our products and the information that they contain. Finally, our site offers numerous interactive data services that provide customized almanac data on demand, free of charge. Prior to the establishment of our Web site, the latter two tasks had to be handled by staff astronomers, resulting in less time available for mission work.

As already implied, our Web site will grow by providing services that complement existing products, especially *The Astronomical Almanac*.

We also plan to further develop and improve a restricted part of our site that specifically serves the needs of our U.S. military customers.

Use of the World Wide Web as a means of disseminating almanac data is perhaps the most important component of our plan for the future.

Summary and Conclusions

The Astronomical Applications Department of the U.S. Naval Observatory plays a unique role in providing practical astronomical data in the U.S. I am unaware of any other organization in the U.S. that provides high precision almanac data via printed books, computer applications, and the Internet. The department will continue to work toward its traditional goals of providing data of high precision and accuracy, to present those data in useful and usable formats, and to provide those data in a reliable fashion. Furthermore, the department plans to undertake new initiatives to revise its products to meet changing user needs. The key elements of our plans can be summarized as follows:

- Despite the widespread use of computers and the rapid development of the Internet as a mechanism for disseminating data, there are still valid reasons and strong demand for printed almanacs.

- USNO has proposed that the U.S. Navy make our STELLA software the primary tool for routine use in celestial navigation, and relegate manual means of sight planning and reduction to a backup role. If this occurs, the AA Department will likely produce an "Abridged Nautical Almanac" for Navy use, to be published every three to five years. HMNAO would continue to produce the current *Nautical Almanac* and ensure its availability in the U.S.

- The future of the U.S. *Air Almanac* is uncertain. Due to declining use of celestial techniques for air navigation, it is likely that the *Air Almanac* will be reduced in scope or terminated within five to ten years.

- In a cooperative venture between the AA Department and HMNAO, *The Astronomical Almanac* will be revised. Planned improvements include incorporating the ICRS, a new ephemeris of the solar system, some improved tables and new material, and elimination of outdated material. The book will also include an electronic component, likely in the form of links to WWW services that extend the usefulness of the printed material. The two offices will also explore replacement of *Astronomical Phenomena* with an expanded publication aimed at a broader market.

-The AA Department will continue to improve and support its computer-based almanacs, MICA and STELLA. Both programs are being revised to be fully compliant with the latest PC operating systems, and new features and functions will added.

-The AA Department is fully committed to making almanac data available via the WWW. Our Web site will continue to be expanded and improved, and will help customers obtain the traditional products, provide answers to frequently asked questions, and provide selected almanac data, especially those data that extend the usefulness of print material.

Last, but certainly not least, the AA Department looks forward to continued successful collaboration with HMNAO and its new parent organization, the Rutherford Appleton Laboratory. Our desire to collaborate has recently been affirmed via a new Memorandum of Understanding between the two organizations to guide our cooperative work.

Acknowledgements

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NOTES

1. G. H. Kaplan, "New Technology for Celestial Navigation," these *Proceedings*.
2. For a concise discussion of the ICRS and its practical consequences, see: M. Feissel and F. Mignard, "The Adoption of the ICRS on 1 January 1998: Meaning and Consequences," *Astronomy and Astrophysics*, **331**, (1998), L33-L36.
3. The Newcomb project is an AA Department effort to produce new fundamental ephemerides of major solar system bodies. Additional

information can be found in the Research section of the AA Department World Wide Web site (<http://aa.usno.navy.mil/AA/>).

4. MICA is USNO's computer-based almanac for high precision applications. For more information concerning MICA (and STELLA), see J. A. Bangert, "The Astronomical Applications Department Today," these *Proceedings*.

CONTRIBUTORS

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The Astronomical Applications Department Today
The Future of Almanac Data in the United States

John A. Bangert is the Head of the Astronomical Applications Department of the U.S. Naval Observatory. His career has included work in satellite geodesy at the Defense Mapping Agency (now the National Imagery and Mapping Agency), a short stint in private industry, and several positions at USNO. Prior to his current position, he served as project manager for *MICA* and *STELLA*, USNO's next-generation computer-based almanacs. Mr. Bangert holds a B.S. degree in astronomy from Villanova University and a M.S. degree in astronomy from the University of Pennsylvania.

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Celestial Navigation by U.S. Civilian Mariners Near the End of the Second Millennium A.D.

William J. Brogdon is a writer, navigation consultant, and expert witness in maritime cases. He has written over 300 articles in major boating magazines and a book on marine navigation. He retired from the U.S. Coast Guard in 1986 with the rank of Captain. During his Coast Guard career, he served on six ships and commanded three. He was the President of the International Loran Association from 1996 through 1998. Captain Brogdon graduated from the U.S. Coast Guard Academy and holds a M.S. degree from Long Island University.

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A History of Women in the Nautical Almanac Office

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Steven J. Dick is an astronomer and historian of science at the U.S. Naval Observatory. He is also President of Commission 41 (History of Astronomy) of the International Astronomical Union, and past Chair of the Historical Astronomy Division of the American Astronomical Society. He is the author of three books and also served as co-editor of *Sky With Ocean Joined: Proceedings of the Sesquicentennial Symposia of the U. S. Naval Observatory*, published in 1983. Dr. Dick holds a B.S. degree in astrophysics, a M.A. degree, and a Ph.D. degree in history and philosophy of science, all from Indiana University.

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The Moon and the Almanacs

Raynor L. Duncombe headed the U.S. Naval Observatory's Nautical Almanac Office from 1963 until 1975, after which he assumed the duties of professor of aerospace science at the University of Texas at Austin. He began his career at the U.S. Naval Observatory in 1942. Dr. Duncombe has published numerous papers, and holds or has held offices in five professional organizations, including the International Astronomical Union and the (U.S.) Institute of Navigation. Dr. Duncombe holds a B.A. degree from Wesleyan University, a M.A. degree from the State University of Iowa, and a Ph.D. degree from Yale University.

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Dr. Alan D. Fiala*The Evolution of the Products of the Nautical Almanac Office*

Alan D. Fiala is the Chief of the Nautical Almanac Office, now a division of the Astronomical Applications Department of the U.S. Naval Observatory. He started in the Nautical Almanac Office as a summer intern in 1962 and has been there since, except for a five-year stint as Deputy Director of the short-lived Orbital Mechanics Department. His research interests include orbits of minor planets, and eclipses of the Sun and Moon. Dr. Fiala holds degrees in astronomy from Carleton College and Yale University.

F. Stephen Gauss*Precise Star Positions for Positioning Applications*

F. Stephen Gauss is the Head of the Astrometry Department of the U.S. Naval Observatory. He came to USNO's Six-inch Transit Circle Division in 1963 where he observed and produced proper motions for the star catalogs. In 1968, he designed and installed the first computer control system on the transit circle. Mr. Gauss holds an undergraduate degree from Cornell University and a Master's degree from Georgetown University, both in astronomy.

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Almanacs: An Astronomer's Perspective

Heidi B. Hammel is a Principal Research Scientist in the Department of Earth, Atmospheric, and Planetary Sciences at the Massachusetts Institute of Technology. She works primarily in the field of outer planets, and has published more than 30 scientific papers. She is an acknowledged expert on the planet Neptune, and was a member of the Imaging Science Team for the Voyager 2 encounter with that planet in 1989. For the impact of Comet Shoemaker-Levy 9 with Jupiter in July 1994, Dr. Hammel led the Hubble Space Telescope Team that investigated Jupiter's atmospheric response to the collisions. Dr. Hammel holds an undergraduate degree from MIT, and a Ph.D. degree in astronomy from the University of Hawaii at Manoa.

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The Newcomb Project: The Database of Solar System Observations

James L. Hilton is an astronomer in the Dynamical Astronomy Division of the Astronomical Applications Department of the U.S. Naval Observatory. He has been working in the field of ephemerides ever since his arrival at USNO in 1986. Recently he produced new ephemerides for fifteen of the largest asteroids and made determinations of the masses of the three largest asteroids. He is currently working on Newcomb, a new high-accuracy ephemerides program. Dr. Hilton holds an undergraduate degree in physics from Rice University and M.A. and Ph.D. degrees in astronomy from the University of Texas at Austin.

The Honorable Jerry M. Hultin

Reception Speech (3 March 1999)

Jerry MacArthur Hultin is the 27th Under Secretary of the U.S. Navy. As the Navy's number two civilian leader, he is directly responsible to the Secretary of the Navy for all matters pertaining to the Navy's manpower, personnel, reserve affairs, installations, finance, environmental issues, and

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Dr. Paul M. Janiczek

A Brief Survey of Modern Navigation

Paul M. Janiczek retired in 1997 after a long career as an astronomer at the U.S. Naval Observatory. Following employment with the Philco Corporation, and the IBM Corporation, he joined the staff of the Nautical Almanac Office in 1967. For eight years he served as editor of the professional journal *Navigation* and brought out two volumes of the Institute of Navigation special publications on the Global Positioning System. In 1990, he was selected as the first Head of USNO's Astronomical Applications Department. Dr. Janiczek holds an undergraduate degree from King's College (Wilkes-Barre, Pennsylvania) and a Ph.D. degree in astronomy from Georgetown University.

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New Technology for Celestial Navigation

George H. Kaplan is Chief of the Dynamical Astronomy Division in the Astronomical Applications Department of the U.S. Naval Observatory. He has been an astronomer at USNO since 1971, and has worked in the Nautical Almanac Office, the Astrometry Department, and the office of the Scientific Director. Dr. Kaplan has completed a wide variety of projects in positional astronomy, and was the project leader for the *Floppy Almanac*, the first high-precision astronomical and navigational almanac program for PCs. Dr. Kaplan holds B.S., M.S., and Ph.D. degrees in astronomy from the University of Maryland.

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Ephemerides of Small Bodies of the Solar System

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Navigation and Precise Time

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A View from the Deckplates

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Simon Newcomb at the Nautical Almanac Office

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Modeling of Planetary Motions: Why We Care and How We Do It

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Lt Col Edward M. Sienkiewicz, Jr., USAF*Celestial Navigation and The Air Almanac in the KC-135R Stratotanker*

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Dr. Susan G. Stewart

Overview of "Connections" Session

Dr. Susan Stewart is the newest member of the Nautical Almanac Office of the U.S. Naval Observatory's Astronomical Applications Department, having joined the group in the summer of 1997. Her primary duty is maintaining *The Astronomical Almanac* to comply with current conventions, theories, and research. She is also responsible in part for maintaining the production schedule of the NAO's annual publications. Her research focuses on star formation in irregular galaxies and ultraviolet astronomy. Dr. Stewart holds a B.S. degree in physics and astronomy from Vanderbilt University, and a Ph.D. degree from the University of Alabama.

Dr. Craig B. Waff

Astronomy and Geography vs. Navigation: Defining a Role for the American Nautical Almanac Office, 1944-1850

Craig B. Waff is Physical Sciences Senior Editor of *Encyclopedia Americana*, published by Grolier Educational in Danbury, Connecticut. His early research dealt with the introduction of gravitational theory into theories of the Moon's motion in the late 17th and early 18th centuries. As a contract historian at the California Institute of Technology's Jet Propulsion Laboratory, he wrote histories of the space agency's Deep Space Network communications system and Galileo space-probe project. Dr. Waff holds a B.S. degree in mathematics from the University of Florida and a Ph.D. degree in history of science from Johns Hopkins University.

Patrick T. Wallace

The Future of Almanac Data in the United Kingdom

Patrick T. Wallace currently has several roles within the Space Science and Technology Department of the Rutherford Appleton Laboratory. He is perhaps best known for his role as manager of the UK Starlink project. During the 1980s, he developed the SLALIB positional-astronomy software library, and as a result, now chairs the International Astronomical Union's Software for Astrometry (SOFA) Reviewing Board.

His time is currently split between Starlink, SOFA, and the Gemini 8-meter telescopes project. In 1998, with the closure of the Royal Greenwich Observatory, he assumed responsibility for Her Majesty's Nautical Almanac Office. Mr. Wallace holds a BSc degree in astronomy from University College, London.

Dr. George A. Wilkins

History of the British Nautical Almanac Office

George A. Wilkins is an Honorary Research Fellow of the University of Exeter and is associated with the Norman Lockyer Observatory. He joined the staff of H.M. Nautical Almanac Office, then part of the Royal Greenwich Observatory, in 1951. He was named Superintendent of HMNAO in 1970, and Head of the Almanacs and Time Division of RGO from 1974 until his retirement in 1989. He has held various offices within the International Astronomical Union and is active in several other professional societies. Dr. Wilkins holds BSc degrees in physics and mathematics and a PhD degree from the Imperial College of Science and Technology, which is part of the University of London.